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DISPLAY CHARACTERISTICS OF EXAMPLE LIGHT-VALVE PROJECTORS

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This report provides quantitative data on performance characteristics of light-valve projectors in simulator displays as well as in optimal laboratory conditions. Two types of light-valve projectors are discussed: a single light-valve projector (also called Talaria) and a multiple light-valve projector. The data show that (a) these projectors do not achieve brightnesses above the mesopic level in large-screen simulator displays, (b) color output includes a "dark-field haze" which must be dealt with like ambient illumination, and (c) light/dark ratios (L/D) above 5:1 are obtainable only when the light region is white or yellow-green.

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SUMMARY

This report presents colorimetric data on the dome and dodecahedron displays used at the Air Force Human Resources Laboratory (AFHRL) for flying training research. The amount of light in these displays varies between 0.23 and 8.5 candelas per square meter when evaluated with respect to photopic visual sensitivity. Light/dark ratios (L/D) in the simulator displays were below 18, except for maximum white versus minimum black. The area-of-interest, but not the background, was able to render the relative luminances of a test scene satisfactorily; neither region reproduced the intended colors faithfully.

Measurements were made on both single (SLVP) and multiple (MLVP) light-valve projectors in a laboratory where the displays were shown on a rear-projection screen. Data on the spectral energy distributions of the three primaries and on the relation between operating voltage and primary luminance ("gamma" function) have been corrected for the influence of a "dark-field haze" resulting from the internal optics of these projectors. The dark field must be considered as a constant additive factor analogous to ambient illumination on a cathode-ray tube.

For both LVPs, luminance of maximum white decreased in the corner regions, measuring from one-third to three-quarters of luminance at the center. Frequent measurements taken over a 5-week period traced the expected gradual decline of luminance with aging of the xenon arc sources, but they showed only minor drifts of chromaticity. Square-wave contrast ratios at 30 pixels per cycle varied from 9:1 for the brightest colors (green and white) to 3:1 for the blue primary at its maximum output.

PREFACE

This report is based on work performed at the Air Force Human Resources Laboratory (AFHRL) at Williams Air Force Base, Arizona. It is part of an ongoing effort to improve color fidelity in flight simulator visual displays, in support of technical program Training Technology, Visual Scene and Display Requirements. The work was conducted by the University of Dayton Research Institute under Contract Nos. F33615-84-C-0066 and F33615-87-C-0012, work unit 1123-32-01. The principal investigator was Dr. Celeste M. Howard. The Laboratory technical monitor was Dr. Elizabeth Martin.

Measurements obtained in the dome and dodecahedron simulators required the assistance of many staff members, most of them General Electric staff engineers and data base modelers. The author gratefully acknowledges the help of Bryce Ericksen, Gale Reining, Richard Olson, Sharon Appler, Jeff Clark, Steve French, Scott Secor, and Mary Ann Tuten. Susan Baroff supervised the collection of the data in Section VI and provided the data summary on which the figures in that section are based. Scott Smallwood, Ron Evans, Norwood Sisson, and David Burba of UDRI and Lt Samuel D. Young of AFHRL/OTA have assisted in computer programming and operation; Mr. Sisson also suggested a useful way of observing the color distortions produced by light valves in some grating pattern displays. George Kelly of CAE Industries Ltd. read an early draft of this report and detected evidence indicating the dark field's importance. Tom T. True of General Electric Projector Display Products Operation, Syracuse, NY, read a short paper (Howard, 1989) based on the results reported here and suggested several improvements in both method and presentation. Drs. Herbert Bell, Elizabeth Martin, Peter Crane, and Wayne Waag of the Human Resources Laboratory, and Dr. Julie Lindholm (UDRI), have helped to clarify the direction of this work; Dr. Bell also read a draft of this report and offered many helpful comments. Roseann Perchinelli prepared the figures, and Marge Keslin supervised production of the manuscript.

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I. INTRODUCTION

Flight simulator displays have acquired color capability, but little is known about the effective use of color in such displays. What are the minimum color requirements for an effective pilot training display? How well do present displays fill these requirements? The information contained in this report is part of an ongoing effort to provide answers to these questions.

At the outset no data were available describing the actual colors in existing simulator displays at the Operations Training Division of the Air Force Human Resources Laboratory (AFHRL). Thus it was necessary to begin by obtaining descriptive measurements. For the present effort, some very simple assumptions were made about minimum color requirements. It was assumed that the brightness, color, and resolution of the displays should be great enough to reproduce the relative luminances and contrasts of scenes designed to test hypotheses about the effect of scene content on pilot training. As the report will show, the present large-screen displays using light-valve projectors do not reproduce scenes designed on cathode-ray tubes (CRTs) very faithfully. Besides having low brightness, which is largely accepted as inevitable at present, these displays have very limited contrast and resolution, and color fidelity is difficult to achieve and maintain even across their restricted range of luminance levels.

Because AFHRL is interested in light-valve projectors (LVPs) as display devices in flight simulators, this examination of LVP display characteristics will emphasize those characteristics which affect the LVP's performance in simulator displays. The characteristics discussed herein may or may not affect the LVP's suitability for other uses, such as large-screen display of television productions or of computer-aided design/computer-aided manufacturing (CAD/CAM) graphics.

The first section of this report introduces the terminology to be used and the technical problems to be addressed, making use of measurements on certain LVPs which were in place at AFHRL as simulator display devices. Observations on the characteristics of such displays serve to raise the essential questions which need to be asked about LVP performance in flight simulators. It should be remembered, however, that individual LVPs have finite use lifetimes, so that the particular instruments discussed in the following section have in many cases already been replaced by other projectors. Furthermore, progress is continually being made in the adjustment and control of LVP color, and the same kind of measurements made today would undoubtedly show improvement in certain respects.

II. CHARACTERISTICS OF AFHRL SIMULATOR DISPLAYS

Attention will be given in this section to three kinds of questions about LVP simulator displays: (a) How much light is available in these displays? (b) What are the resolution and contrast limits of these displays? and (c) How faithfully do they reproduce the colors which the scene designers intended them to display?

Measurements of Luminance Levels

To answer questions about the amount of light available, measurements must be made of radiant energy (radiance) within the visible spectrum (390 to 730 nanometers). However, it is not sufficient merely to report the physical energy available, because the human visual system is not equally sensitive to all wavelengths within the visible spectrum. We are not so much interested in radiance as in luminance, which is light energy evaluated in terms of its effectiveness as a stimulus for the eye. To calculate luminance, we must give the energy in each wavelength region a weight which is proportional to the sensitivity of the human eye to that wavelength. When this has been done, we speak of luminance, and the units in which luminance is commonly measured are footlamberts (ftL) or candelas per square meter (nits). For this report, luminance measurements will be expressed in nits. A footlambert is equal to 3.426 nits.

Two types of instruments are in use at AFHRL for the measurement of luminance: the Pritchard photometer and the Photo Research 703A Spectrascan. Both instruments give readings based on the response of photodiodes to light coming from a small area of the display.

The Pritchard photometer offers a choice of several aperture sizes: 3°, 1°, 20', 16', and 2' visual angle. Light from a display area of the chosen size passes through a special filter before reaching the photodiodes. This filter has been carefully crafted to match as closely as possible the human visual efficiency function for daylight or photopic vision, commonly called $V(\lambda)$. An idea of the shape of $V(\lambda)$ can be obtained from Figure 1, which also indicates the shape of the similar function $V'(\lambda)$ for night vision and the relation between these two functions.

A filter designed to match $V(\lambda)$ is called a photopic filter. Thus the response of the photodiodes to the display light will vary with the color of the light in a manner proportional to the response of the human eye, provided that the light level is in the daylight range. The Pritchard photometer gives continuous readings in units of footlamberts. It is a fast and convenient instrument. Its accuracy is limited by the accuracy with which its photopic filter matches $V(\lambda)$, and it provides no detailed information on the spectral energy distribution (SED) of the display light being evaluated.

The Photo Research 703A SpectraScan is a spectroradiometer controlled by a microcomputer. Its aperture is a rectangle 0.5 degree in height and 1.5 degrees in width. Light from the display passes through a diffraction grating which spreads the wavelengths over an array of 171 photodiodes,

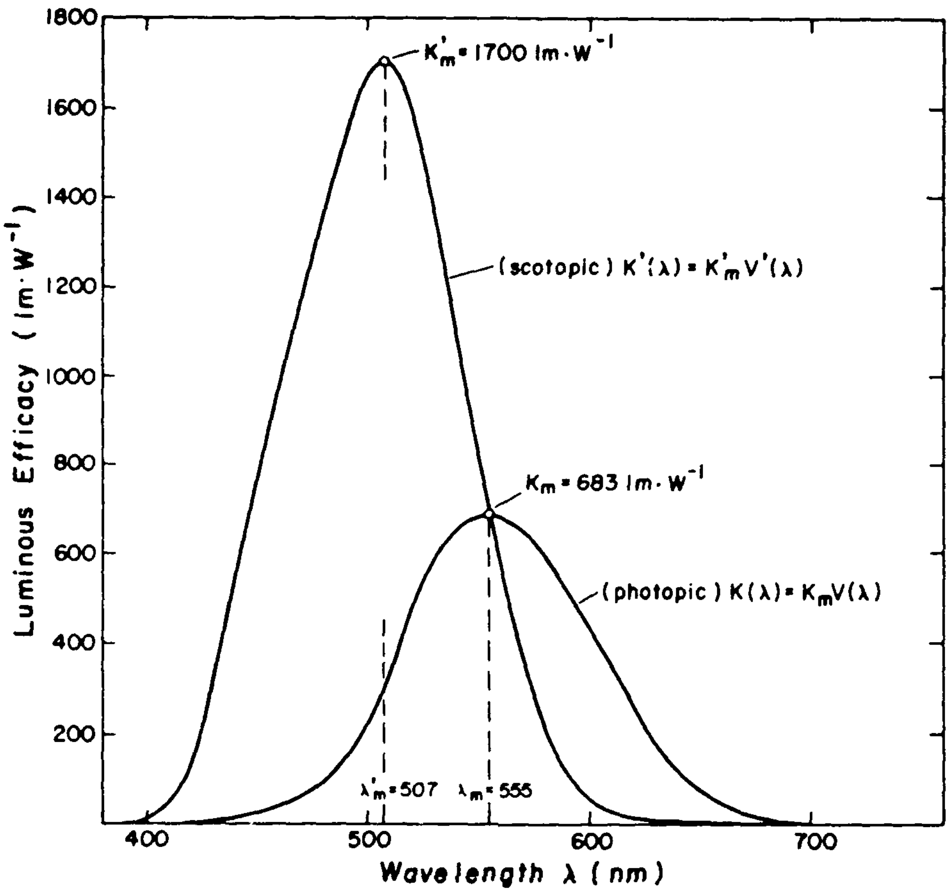


Figure 1. Spectral Luminous Efficacy Functions for Photopic and Scotopic Vision. The human visual efficiency functions $V(\lambda)$ and $V'(\lambda)$ have been multiplied by their respective constants, K_m and K'_m, converting the functions to the same scale in units of lumens per watt. Peak sensitivity is at 555 nm for the photopic function and at 507 nm for the scotopic function. (Reproduced by permission from G. Wyszecki and W. S. Stiles, Color Science: Concepts and Methods, Quantitative Data and Formulae, 2nd Edition. New York, Wiley, 1982, p. 258.)

each receiving light within a particular 2-nm range of the visible spectrum. After making a dark-light correction, the computer writes a file giving the radiance in watts per steradian per square meter per nanometer for each 2-nm interval. It also computes from this file a number of descriptive statistics, including luminance. The radiometer can evaluate luminance using either the standard $V(\lambda)$ function, which is recommended for the measurement of small visual fields up to 4 degrees of visual angle (VA), or the 10-degree visual efficiency function, which is recommended for measuring larger visual fields. The need for more than one visual efficiency function, even at daylight levels, can best be understood by remembering that the human fovea, which contains only cones,

subtends no more than 2 degrees and lies at the center of clear vision. Larger fields will therefore stimulate increasing proportions of rods as well as cones, and the luminous efficacy function for rods (represented by the K'(λ) function in Figure 1) differs markedly from the luminous efficacy function for cones.

It might seem that the radiometer would always be the instrument of choice since it gives so much more information than does the photometer. Indeed, use of the radiometer is essential for any evaluation which requires information about display chromaticity. However, for simple luminance measurements, the photometer is faster, especially at very low light levels, and its accuracy can be maintained by regularly calibrating it against simultaneous measurements made with the radiometer. Luminance measurements with the radiometer may take several minutes when the luminance is below 5 nits, and such measurements are also subject to greater error as luminance decreases.

Table 1 shows the results of measurements made in March 1987 on displays in the F-16 dome and A-10 dodecahedron at AFHRL. The dome display has two separate projector systems, one for the 140° x 60° background of the scene and the other for the 26° x 20° central region or area-of-interest (AOI), in which resolution is higher. The background projector system actually contains two LVPs in order to achieve a satisfactory brightness match with the smaller AOI display.

The dodecahedron has seven LVPs, each projecting through special optics onto one of seven screens which together give a 180° x 270° field of view. Measurements were made on the central screen of the display.

The image generators used to control AFHRL displays all permit 256 voltage levels for each primary, specified by numbers from 0 to 255. A three-number digital code makes up the message which is sent from the image generator to the digital-to-analog converter governing voltage. The first number governs voltage of the red primary, the second governs that of the green, and the third, that of the blue. Since the red-green-blue order is important, the digital code is often called an RGB code.

Each display was measured at several operating voltages, as determined by the RGB code. These operating voltages will be referred to as video levels, so that we may speak of the operating voltage of red when the RGB code is 63,0,0 as "red video level 63." "White video level 63" thus means that all three primaries are operating at video level 63, in response to digital code 63,63,63. Thus, the signal 0,0,0 means no red, green, or blue output; its result is the "dark field." The signal 255,255,255 results in maximum output of all primaries.

Luminances in Table 1 range from 0.23 nit for the dark-field haze of the dome background to 8.34 nits, the luminance of white video level 255 in the AOI. These values should be considered in relation to Figure 2, which gives the luminance ranges corresponding to sunlight, moonlight, and starlight vision. The luminance levels shown in Table 1 lie well within the mesopic range of vision.

Table 1. Display Luminances in Nits

Display area	Video level	Red alone	Green alone	Blue alone	White (R+G+B)
Dome Background	0 ("Black")				0.23 (dark field)
	63	0.27	0.56	0.26	0.62
	127	0.58	2.92	0.55	3.35
	191	0.92	4.57	0.69	5.46
	223	0.94	4.93	0.77	5.72
	255	1.06	5.27	0.84	6.29
Dome AOI	159	1.51	7.02	1.18	7.31
	191	1.80	7.12	1.30	7.62
	255	2.05	7.02	1.44	8.34
Dodec	159	0.55	3.71	0.65	3.32
	223	0.87	4.34	1.01	4.89
	255	1.04	4.32	1.13	5.08

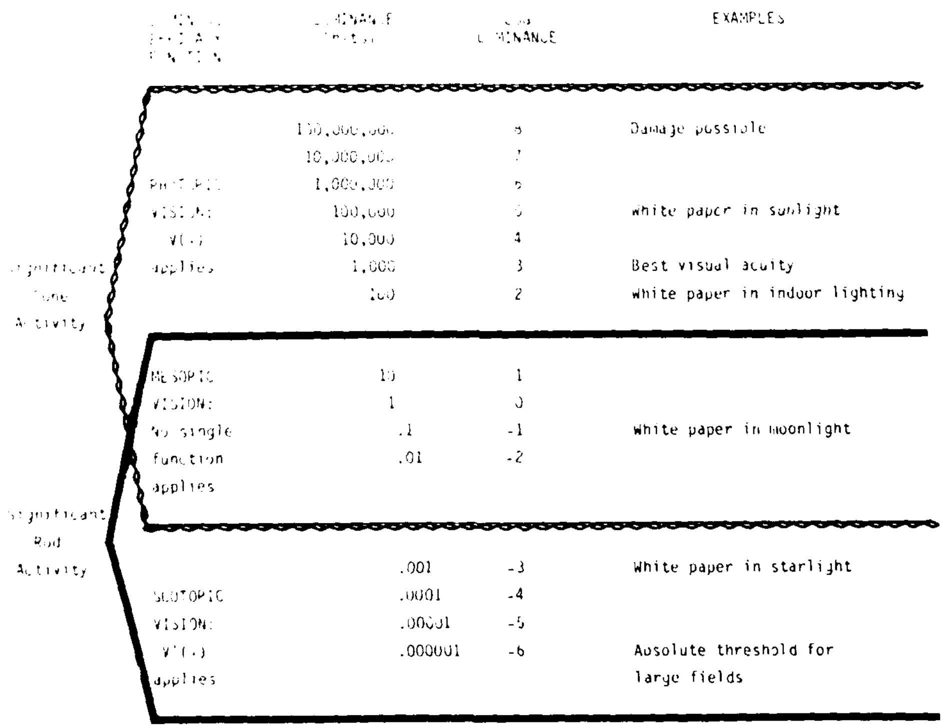


Figure 2. Luminance Ranges for Photopic, Mesopic, and Scotopic Vision. (Adapted from Ken Miller, "Standardizing color CRT measurements for avionics and computers." Test and Measurement World, April 1984.)

It should be remembered that these measurements were made on LVPs _in situ_ in simulator displays. Much greater luminances can be obtained from LVPs under other display conditions, as later sections of this report will show. Two factors account for the loss of light in the simulator displays represented above: (a) the display optics, which absorb a great proportion of the projected light; and (b) the large area filled by the background display in the dome.

Because these luminances are not in the range of daylight vision, they cannot be taken without modification as accurate indicators of the apparent brightness of the displays. They should be understood as _photopic luminances_; that is, luminances evaluated with respect to visual _sensitivity under_ daylight conditions. Accurate evaluation of the apparent brightness of areas in these displays will require a method of mesopic photometry, and at the present time no officially accepted method exists. For the moment, it should merely be noted that the light level in these displays is more like bright moonlight than it is like a daylight scene.

The data in Table 1 have another interesting feature. In order to predict display luminance from the digital code, it is customary to rely on addition of the three primary luminances at their respective video levels. This method of luminance prediction works reasonably well for CRTs. However, it seems from the data in this table that the method will not work for the LVP, since the sum of the R, G, and B values for each line yields a luminance prediction that is as much as 76% _greater_ than the luminance actually measured for the white R+G+B combination.

The reason for this discrepancy lies in the dark-field haze, which was measured only for the dome background in Table 1. The dark field is the lowest luminance obtainable in any LVP display scene. Yet for this display the dark-field luminance is almost as large as the red or blue output at video level 63. Since 0.23 nit is already present with a digital code of 0,0,0, each of the 21 luminances for the dome background contains the dark-field haze of 0.23 nit, plus whatever color is added by the non-zero part of the RGB code. When the dark-field component is removed from each of the background luminances in Table 1, the RGB sum provides a much better estimate of the white luminance.

Contrast and Resolution Measurements

In May 1987 final preparations were being made for an object density study (Kleiss, Hubbard, & Curry, 1989). The experimental conditions called for a comparison of three types of objects, each appearing in the data base at three density levels. In order to make the comparison of object-type meaningful, it was necessary to ensure that all three types (pine trees, oak trees, and tetrahedrons) were of similar luminance and contrast.

Measurements were made on all three types of objects as they appeared in the dome display. The Photo Research PR719, a spatial scanning radiometer, was used to scan across each type of object and its

Table 2. Luminance and Contrast of Objects in Object Density Study

Object	Display area			
	AOI		Background	
	Peak luminance (nits)	L/D Ratio	Peak luminance (nits)	L/D Ratio
Pine Tree[a]	4.76	2.5	3.47	2
Tetrahedron[a]	8.53	1.7	5.35	1.7
Oak Tree[a]	5.07	2.0	3.59	1.6
Pine Tree[b]	4.83	4.4		
Tetrahedron[b]	5.28	4.7		
Oak Tree[b]	4.70	5.0		

[a]Before texture adjustment.
[b]After texture adjustment.

immediately adjacent background. The PR719 scanner is similar in its design to the Photo Research 703A SpectraScan described on page 3. Its aperture is also a 1.5° x 0.5° rectangle, but in this case light from the display passes through a photopic filter to an array of 125 photodiodes, each receiving light from a different position within the 1.5° aperture. After making a dark-light correction, the computer writes a file giving the luminance in footlamberts for each of the 125 intervals across the aperture. It also provides various statistics on the amount of contrast between peak luminance (in this case, the ground behind the object) and minimum luminance (center of the object). (See Appendix B for an explanation of measures commonly used in describing display contrast.)

Table 2 shows the maximum luminance in nits and the light/dark ratio for each type of object in each of the two areas of the dome display. The top three lines in the table show that the object types differed considerably in both luminance and contrast. Initially no object had an L/D ratio greater than 2.5. In order to meet the conditions of the experiment, efforts were made to equalize luminance and contrast among these objects. All of these objects had been given cell texturing (also known as photo-digitizing or photo-texturing); the tetrahedrons had been given texturing of the same kind as the trees. Using the Pritchard photometer and measuring both peak and minimum luminance for each object, adjustments were made in the cell texturing and color of the tetrahedron until all three object types displayed about the same luminance and contrast. These measurements appear in the bottom three lines of Table 2. The maximum L/D ratio attained was 5.

These contrast ratios may be surprising when it is recalled that Table 1 shows an L/D ratio of 6.29:0.23, or approximately 27, for maximum white versus dark field in the dome background. Since the Table 1 measurements were made consecutively on very large areas, they should, and do, correspond to the nominal values often quoted as Talaria's maximum contrast. The Table 2 data, on the other hand, were measured for relatively small dark areas on a light background, and these areas had to appear dark green on a yellowish-tan ground. Therefore, the L/D ratios in Table 2 give a better idea of the contrast likely to be achieved between adjacent colors in a complex scene.

Measurements giving a more complete picture of LVP contrast and resolution will be presented later in this report. However, it is clear even from these preliminary measurements that the LVP displays in the dome are not likely to provide L/D ratios much greater than 4 or 5. These simple measurements also make another point: Luminance and contrast are highly dependent not only on the color but also on the type of cell texturing chosen for a display region.

Scene Color Study

The previous sections introduced terminology and preliminary data concerning luminance and contrast in simulator displays. This section will introduce terminology and data concerning color rendering in those displays.

Simulator scenes are generated from a data base that contains geographical and cultural features. Each feature is assigned one index number which identifies an entry in the color table for that data base. The color table contains a three-number digital code (the RGB code) corresponding to each index number. An image generator uses these codes to control the mixture of red, green, and blue light in each scene area. The image generator for dome and dodecahedron displays at AFHRL is the Advanced Visual Technology System (AVTS).

Modelers creating a data base view the scene on a CRT which serves as monitor for the AVTS. They adjust RGB codes according to their experience with previous data bases and according to the appearance of the scene on the CRT. Assuming that the colors seen on the CRT represent the colors desired in the simulator display, how faithfully does the dome display reproduce these colors?

No general answer can be given to such a question, since the answer will depend on the particular scene selected. Furthermore, the answer will vary from time to time for the same scene because the LVP's operating characteristics are not yet well controlled. However, considerable insight into the fidelity of color rendering can be obtained from a simple experiment.

For this experiment, a data base modeler selected a single scene from a data base; it was specified that the scene should contain some white, gray, and black features, as well as a few colors. Figure 3 is a black-and-white sketch of this scene. The areas studied have been marked

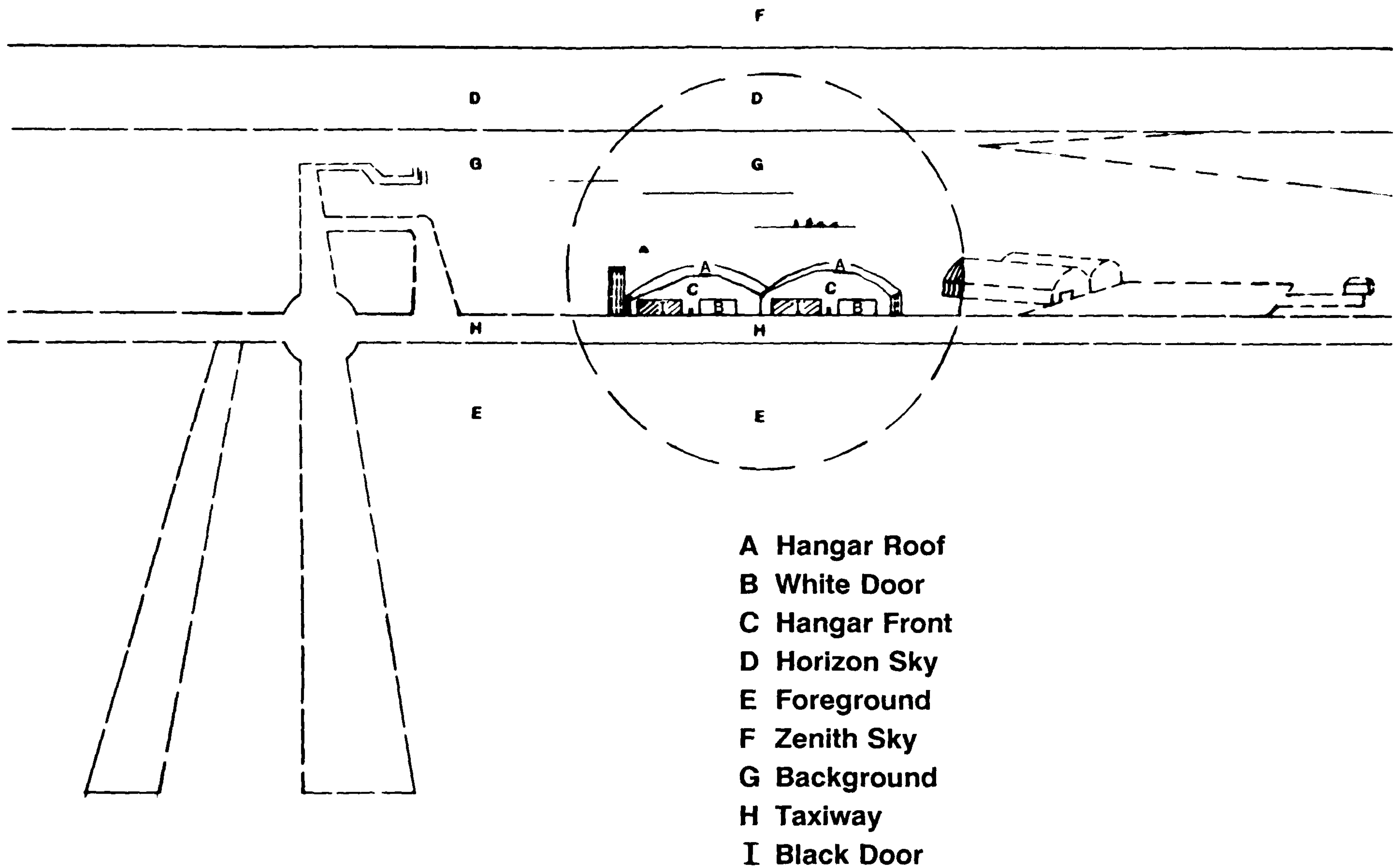


Figure 3. Sketch of Scene Used in Scene Color Study. Central circle (not outlined in actual display) represents the area of interest (AOI). Letters indicate the positions at which measurements were taken.

with letters A through I in sequence from lightest to darkest. Some parts of the scene appeared only in the dome background; others appeared only in the AOI.

Colorimetric measurements were made of each of these nine areas as they appeared in the dome display and on the CRT monitor, which was a Mitsubishi Model C6912 manufactured in 1982. These measurements permit objective specification of the colors of these areas as values of three parameters. These three parameters can be expressed in several forms: as the tristimulus values X, Y, and Z; as luminance (Y) and two chromaticity coordinates in x,y chromaticity space; and as luminance (Y) and two coordinates u' and v' in uniform chromaticity space (UCS). Any one of these sets of three parameters can be converted to any of the other sets by the equations provided in Appendix A.

Figure 4 shows the locus of spectral colors, the purple boundary, and the locus of black body radiators in the x,y chromaticity space established in 1931 by the Commission Internationale de l'Eclairage (CIE). The spectrum locus is the curve drawn to connect points representing wavelengths from 380 to 770 nm; the purple boundary is the straight line connecting the ends of this curve. Positions are also indicated in Figure 4 for tungsten light at 2854^{o}K (Standard Illuminant A), for white light with equal energy at all visible wavelengths (E), and for daylight at 6500^{o}K (D65). At present, the generally preferred reference white is D65. Figure 5 shows these same reference colors in the uniform chromaticity space (UCS) recommended by the CIE in 1976.

The question of color fidelity can be divided into two parts: (a) How faithfully does the dome display reproduce the position in color space of each area on the monitor? and (b) How faithfully does it reproduce the relative luminance of these areas? Table 3 lists the luminance (Y) and u',v' chromaticity coordinates obtained for the nine areas indicated in Figure 3. The values of u',v' coordinates answer the question about position in color space; information about relative luminance can be derived from the Y-values.

Figure 6 shows the u',v' coordinates plotted in a UCS diagram. Color points from the CRT are shown as crosses. Points from the dome AOI are shown as squares, and these squares are connected by lines with the corresponding CRT crosses. Points from the dome background appear as triangles and are connected with their CRT crosses by dashed lines.

Six of the CRT points lie very close together in UCS space. These are the white, gray, or black areas (A, B, C, H, and I), and the horizon sky (D) which is modified toward a neutral white by AVTS. On the CRT, these six areas differ from each other mainly in luminance; their chromaticity differences are very small. But when the same digital codes are applied to the dome displays, all of these areas change chromaticity, moving away from the achromatic region. Moreover, they move in several quite different directions, largely as a function of luminance: The dimmer areas become bluer, the areas of medium brightness become more greenish, and the brightest areas become more yellow-green. Such shifts can be observed in the dome as a tendency toward yellowish green in the horizon sky and toward bluish purple on the taxiway.

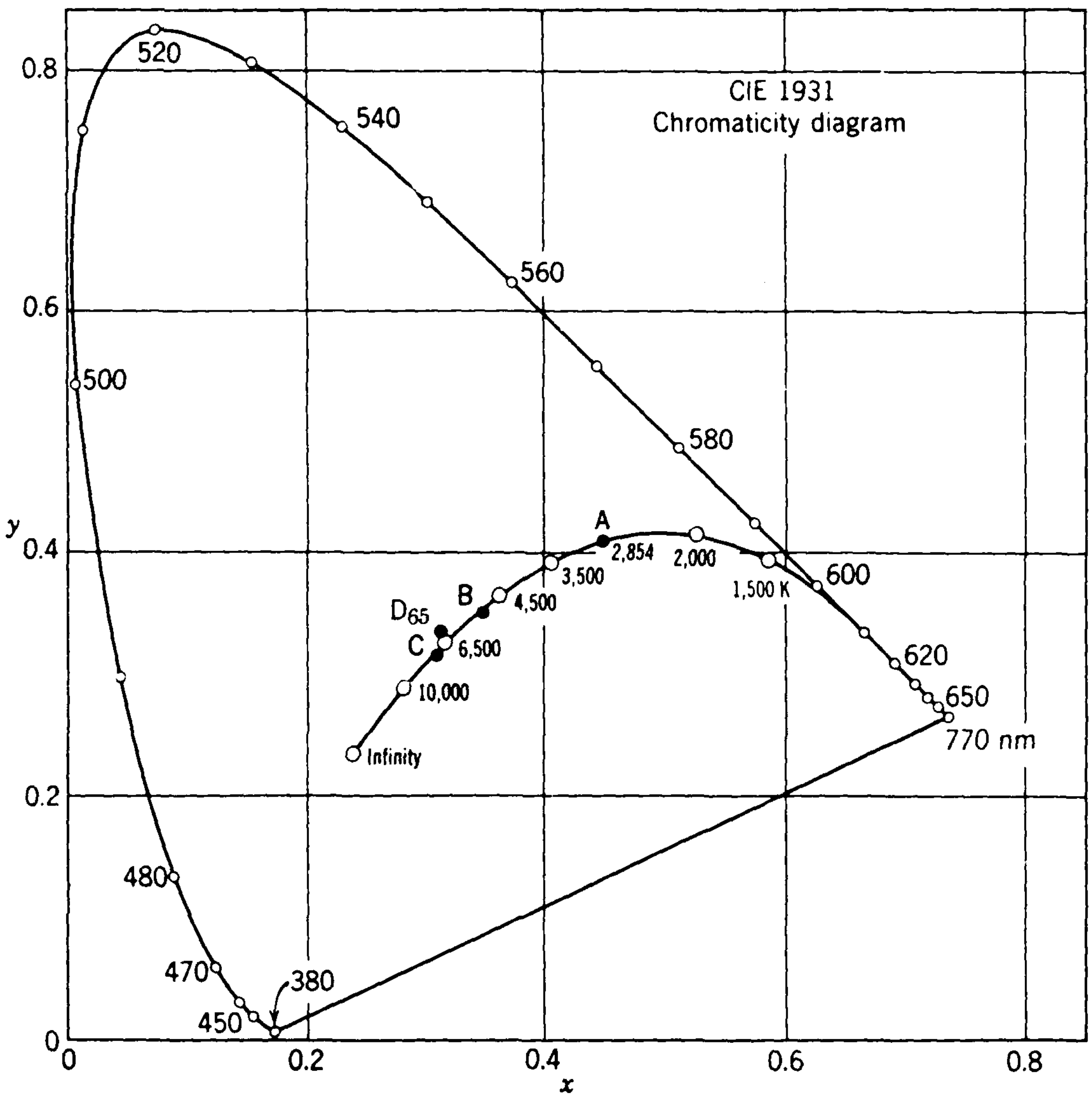


Figure 4. Spectrum Locus and Purple Boundary in the 1931 CIE Chromaticity Space. This space is based on color-matching data using 2° fields. The inner curve is the Planckian locus showing the chromaticity of blackbody radiators at the indicated temperatures (in degrees Kelvin). Also shown are the chromaticity points of CIE standard illuminants A, B, C, and D65. (Reproduced by permission from D. B. Judd and G. Wyszecki, Color in Business, Science and Industry, 3rd edition. New York, Wiley, 1975, p. 166.)

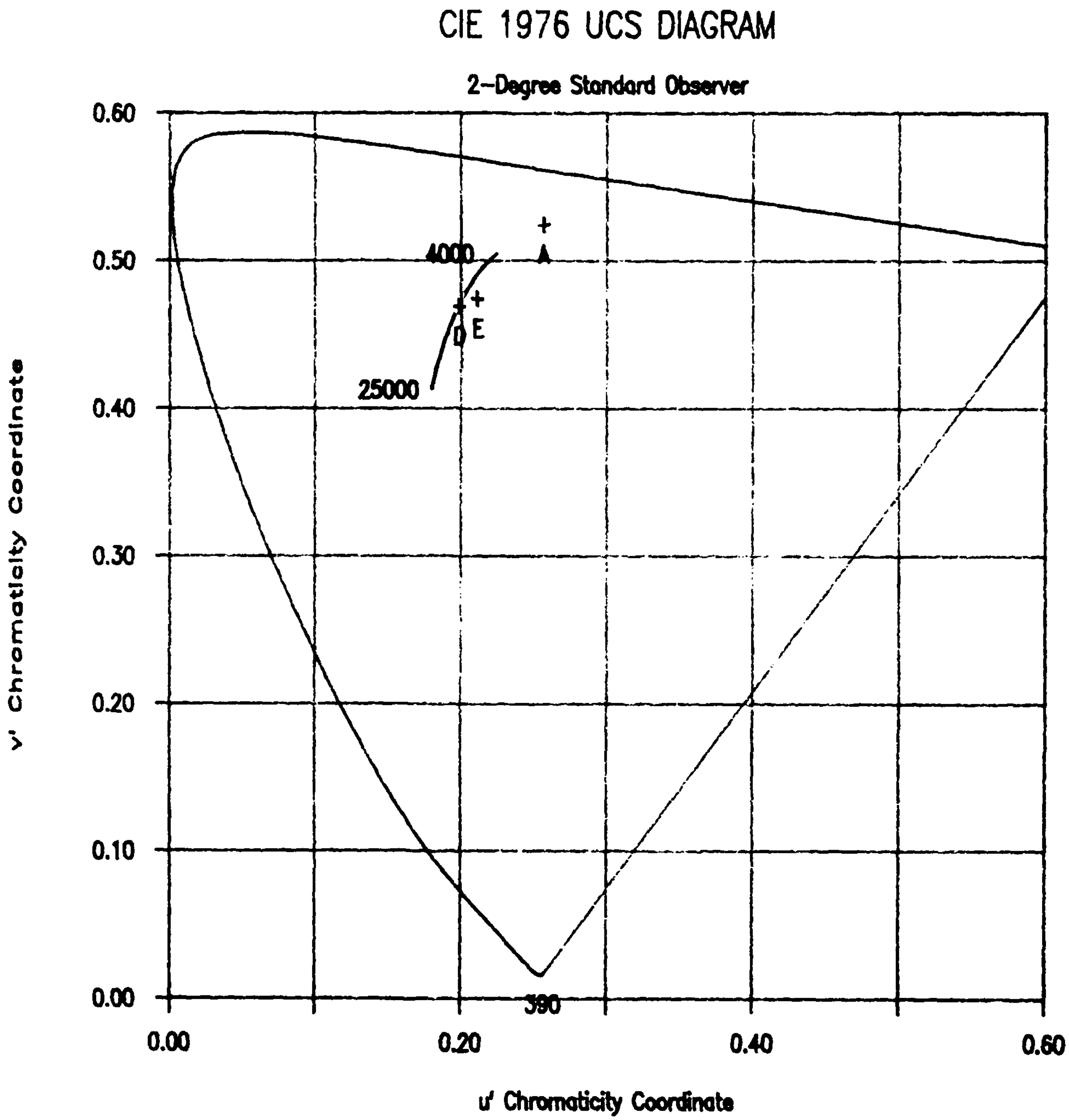


Figure 5. Spectrum Locus and Purple Boundary in the 1976 CIE Uniform Chromaticity Space (UCS). Also shown are the Planckian locus between 4,000° and 25,000°K, the chromaticity points of illuminants A and D65, and the chromaticity point for an equal energy spectrum (at E). This space is a linear transformation of the space shown in Figure 4.

Table 3. Scene Color Study

Scene area		Device								
		Mitsubishi CRT			Dome AOI			Dome background		
Description	RGB code	Y(nits)	u'	v'	Y(nits)	u'	v'	Y(nits)	u'	v'
A: Hangar Roof	180,180,180[a]	460.5	.1973	.4528	5.60	.1705	.5069	Not in background		
B: White Door	180,180,180[a]	371.3	.1852	.4586	7.32	.1713	.5071	Not in background		
C: Hangar Front	180,180,180[a]	304.7	.1913	.4518	6.00	.1701	.5046	Not in background		
D: Horizon Sky	22,77,160[b]	179.9	.1884	.4510	3.05	.1655	.4935	1.94	.1636	.4495
E: Foreground	130,90,27	111.4	.2386	.5336	1.57	.2312	.5256	1.57	.2065	.5410
F: Zenith Sky	22,77,160[b]	62.7	.1744	.2918	Not visible in AOI			0.26	.1445	.1833
G: Background	70,70,0	52.2	.1973	.5395	1.24	.1777	.5170	0.66	.1714	.5215
H: Taxiway	120,120,115[c]	40.5	.1848	.4485	0.42	.1558	.4041	0.24	.1610	.4017
I: Black Door	16,16,16	6.4	.1883	.4514	0.31	.1552	.4308	Not in background		

[a]The color table contains a single code (180,180,180) for areas A, B, and C; this code is modified by AVTS depending on sun angle. The following columns demonstrate how these modifications affected the output colors on the Mitsubishi monitor. The same modifications were made for the dome displays, but the table clearly shows that they did not produce the same color output.

[b]The color table contains a single code (22,77,160) for both sky regions; this code is modified by AVTS to make the horizon sky brighter than the zenith sky. In this case, also, the table indicates that the modifications did not affect all three displays in the same way.

[c]The color code 120,120,115 would be expected to produce a greater luminance than was actually measured in the runway area on any of the three displays; after all, this code has higher numbers than the G area code, which has a higher measured luminance. The reason for the discrepancy lies in the cell texturing of the display areas. Areas E, G , and H are all "cell textured"; the texture chosen and applied to area H is a "darker" texture, which cuts down the luminance more than the "lighter" textures applied to areas E and G.

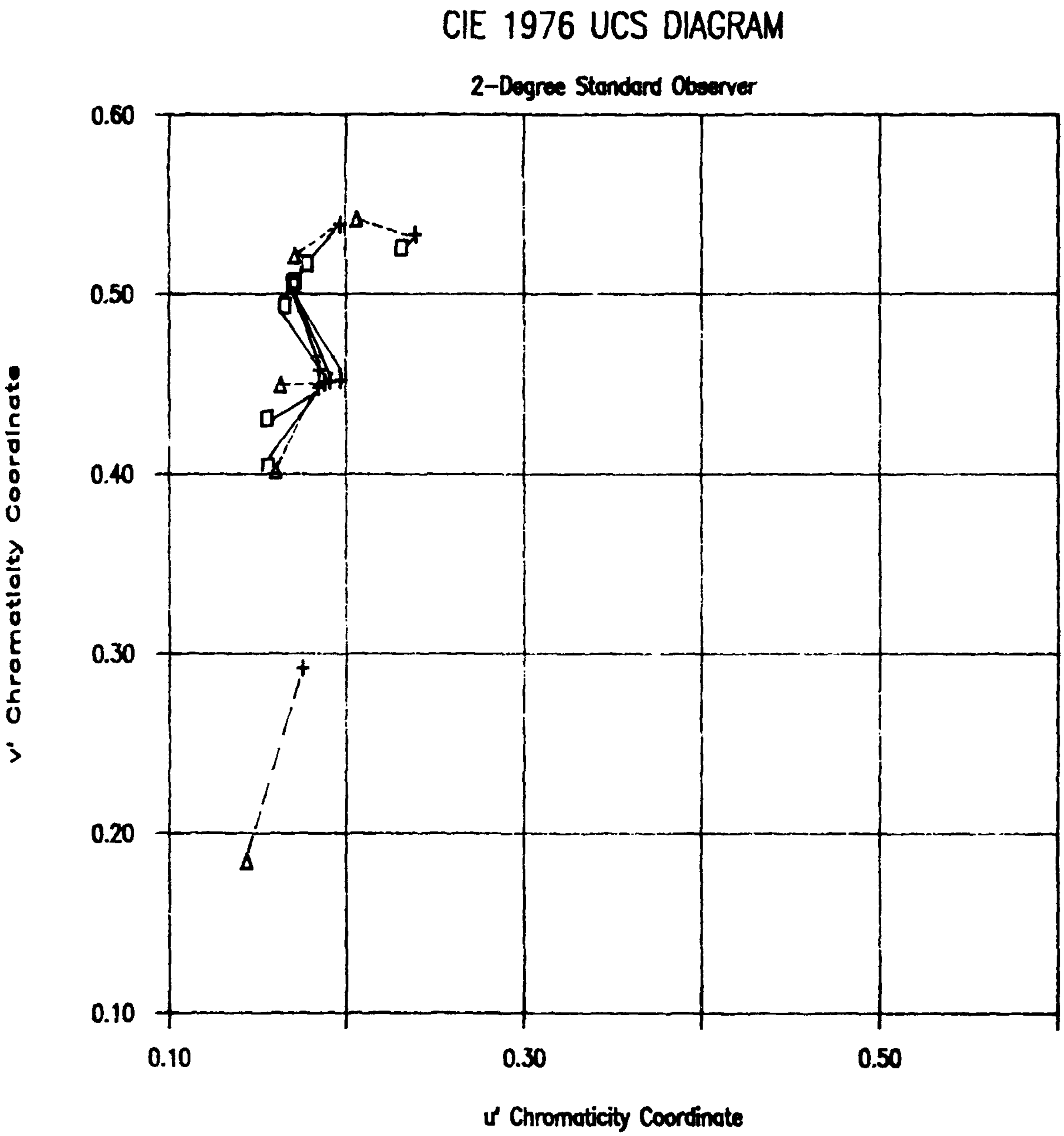


Figure 6. Chromaticity Points of the Nine Colors from the Scene Color Study. Crosses show the colors as measured on the modelers' Mitsubishi CRT, squares as measured in the dome AOI, and triangles as measured in the dome background. Corresponding points in the CRT and AOI displays are connected by solid lines; corresponding points in the CRT and background displays are connected by dashed lines.

Table 4. Luminance Factors in Scene Color Study

Scene area	Mitsubishi CRT Y (nits)	Mitsubishi CRT L.F.	Dome AOI Y (nits)	Dome AOI L.F.	Dome background Y (nits)	Dome background L.F.
A. Hangar Roof	460.5	.80	5.599	.61	Not visible	
B. White Door	371.3	.65	7.319	.80	Not visible	
C. Hangar Front	304.7	.53	5.998	.66	Not visible	
D. Horizon Sky	179.9	.31	3.046	.33	1.940	.21
E. Foreground	111.4	.19	1.566	.17	1.574	.17
F. Zenith Sky	62.7	.11	Not visible		0.256	.028
G. Background	52.2	.09	1.239	.135	0.657	.072
H. Taxiway	40.5	.07	0.424	.046	0.235	.026
I. Black Doorway	6.5	.01	0.308	.034	Not visible	

Colored areas (E, F, and G) also undergo chromaticity shifts. The blue sky at zenith (F) gets darker and bluer when it is applied to the dome background. The ground behind the hangars (G) becomes less colorful and somewhat greener. The yellowish foreground (E) is reproduced well in AOI, but in the background it is decidedly greener.

The dome display has no capacity to duplicate the absolute luminances of the CRT; its luminance range is much too low. However, natural scenes can be reproduced faithfully within many different luminance ranges, provided the relative luminances of their elements are preserved. In order to compare the relative luminances of the dome display with those of the CRT, Table 4 provides the luminance data in terms of luminance factor. This concept requires a brief explanation.

Natural scenes are made up of reflective surfaces which are viewed in a particular illuminant or combination of illuminants. These surfaces reflect different proportions of the light incident on them, and they usually are spectrally selective--that is, the proportion of light reflected is dependent on the wavelength of the light. The variation of reflectance with wavelength is called the spectral reflectance distribution (SRD) of the surface. Spectrally selective reflectors are perceived as having color. When a surface reflects all wavelengths about equally, the SRD is flat, and the surface is said to be "neutral" or "gray." If such a neutral surface reflects at least 80% of the incident light, it will be called "white" or "light gray" by a normal observer. If it reflects 3% or less, it will be called "black." Neutral surfaces that reflect between 3% and 80% of the incident light will be called various shades from dark gray to light gray.

When light reflected from such an illuminated surface is measured, its luminance can be expressed as a proportion of the light which would be reflected in the same direction from a perfect reflecting diffuser in the

same illumination. This proportion is called the reflectance factor of the surface. Although the light from luminous displays is not reflected light, a similar term is needed in describing natural scenes simulated by such displays. The term in common use is luminance factor.

Since the brightest white in a natural scene will normally have a reflectance factor around .80, Table 4 assigns a luminance factor of .80 to area A as seen on the CRT. If a luminance factor of .80 corresponds to 460 nits, then area B with luminance 371 nits has a luminance factor of .65, and so on. All other areas (including background areas) are assigned luminance factors relative to this same scale.

In general, the luminance factors characteristic of the CRT scene are fairly well reproduced in the dome AOI; the brighter and dimmer areas remain in about the same relative positions. Because the dome background is generally dimmer, most of the areas seen in the background have luminance factors that are too low.

It should be noted that large areas such as E and G do not have uniform luminance throughout the background, but tend toward lower luminances at the edges of the display. This non-uniformity is not reflected in Table 4 because measurements for this table were made only at the positions indicated in Figure 3.

Conclusions

From this survey of display characteristics in the dome and dodecahedron, several important findings emerged:

1. Luminance levels in these displays are in the mesopic range. This has two important consequences for display evaluation. First, it must be remembered that the light available in the scene is more like moonlight than like daylight, no matter what type of scene is being represented. The operator will need 5 or 10 minutes of dark adaptation to maximize his/her visual sensitivity.

Second, it must be remembered that any measurements of scene luminance made with current methods will represent photopic luminance; that is, luminance evaluated with respect to standards which apply to daylight vision. When the scene is mesopic, relative photopic luminances of different scene elements are not likely to correspond to the relative brightnesses of the elements as seen by the observer. Until a satisfactory method of mesopic photometry is available, relative brightnesses cannot be accurately measured by photometric instruments and must be directly evaluated by psychophysical observations. A CIE committee has recently recommended that several methods of mesopic photometry be empirically evaluated, and other work in progress at AFHRL will contribute toward this evaluation.

2. Object to background contrast in these displays is not likely to exceed L/D ratios of 4 or 5, except for large black objects on a white ground. Even with black on white, the highest L/D ratio will not exceed 18. Both contrast and luminance will be dependent on the type of texturing, as well as on the color table used.

3. The luminance factors of scene elements are reproduced better in the AOI than in the background of the dome display. If we wish to simulate a scene which has both white and black areas, the L/D ratio between the white and black areas should be about 80:3 (approximately 27). Even when a ratio of 18 was achieved in the AOI, it was accompanied by a chromaticity shift of the white area toward yellow-green and the black area toward blue. To some extent, there appears to be a tradeoff between color fidelity and range of contrast in this display: Adequate contrast can be obtained only with some sacrifice of color fidelity.

III. LIGHT-VALVE PROJECTOR PRIMARIES

For more detailed study of LVP performance, it is useful to employ a projector that is controlled by a less complex image generator than the AVTS. A single light-valve projector (SLVP, or Talaria) connected to an IRIS graphics computer system has been available for study at AFHRL since April 1987. For measurements to be reported in this section, the display was projected onto a rear-projection screen with a gain of unity, located about 4 feet from the projector lens. Measurements were made from the front of the screen, with the radiometer positioned about 13 inches from the screen and focused carefully.

All colors available in these displays are produced by the additive combination of red, green and blue primary colors. This additive principle is also used in CRT displays, where the three primaries are achieved by exciting red, green, or blue phosphor dots placed on the display surface. No phosphors are employed in Talaria. Instead, the three primaries are extracted from the light of a single xenon arc source. This light passes through a dichroic filter, which separates it into green and magenta components.

In order to reach the screen, the green light must pass through two sets of horizontal slits, one near the source and one near the final lens. Between these sets of slits, there is an assembly containing a thin oil film which plays a role analogous to the transparency in a slide projector. The entrance and exit slits are adjusted so that almost no green light will pass through unless there is a change in the oil film. The charge to deform this film is provided by an electron beam, corresponding to the raster-scanning device of a CRT. As the beam sweeps over the oil film, it deposits amounts of charge which differ according to its dwell time and which deform the film. These deformations, whose locations correspond to the desired pattern of green in the display, bend the green light enough to allow it to pass the horizontal exit slits.

Red and blue light must pass through vertical entrance and exit gates in an exactly analogous manner. The horizontal component of the diffraction pattern bends red or blue light, allowing it to pass the vertical exit gate. The carrier frequency differs for red and blue, and the pattern of oil deformation determines the amount of red and/or blue which will pass through the exit gate.

Spectral Energy Distributions

Description of the LVP primaries will begin with their spectral energy distributions (SEDs). Figures 7, 8, and 9 show the SEDs of Talaria's red, green and blue primaries as measured in April 1987. These figures show absolute radiance values in watts per steradian per square meter per nanometer. Complete distributions were recorded at each of six voltage levels for each primary; the dark-field haze is present in each of these distributions. The distributions for red and green, especially at the lower voltages, show periodic ripples which are characteristic features of light-valve projector SEDs. These ripples arise from interaction between the wavelength of the light and the thickness of elements in the oil film assembly.

LVP output is affected by the manner in which the projector's electronic and optical controls have been adjusted. Figure 10 contains data from later measurements, after the light-valve in this projector had been replaced. The LVP was then studied on two occasions, with adjustment to two different luminance ranges. The two upper graphs were obtained when the projector was adjusted to a low range (maximum luminance about 190 nits). The left graph shows SEDs for the dark-field haze (RGB code 0,0,0) and for the green primary at a relatively low video level (RGB code 0,31,0). Diamonds outline the SED of the green primary at this level; this SED necessarily includes the dark-field component. A continuous line indicates the SED for the dark field alone, and crosses show the remainder of the green primary measurement when the dark-field component has been removed by subtraction.

The graph at upper right in Figure 10 shows SEDs of the SLVP's red, green, and blue primaries at the maximum video level (255). The dark field component has been subtracted from each of these distributions. The two lower graphs give corresponding information about this same SLVP, adjusted to give a higher maximum luminance near 430 nits. Comparison of the left graphs at top and bottom shows that the dark-field SED is very sensitive to adjustment of the projector's controls, although the primary SEDs shown at the right remain about the same.

These spectral energy distributions are continuous distributions, without the spikes characteristic of CRT phosphor emissions (particularly red phosphors). In this respect, they are more like the primaries obtainable by passing tungsten light through glass or gelatin filters.

Relationship Between Voltage and Light Output

Accurate manipulation of display color requires careful study of the way the output of each primary varies as operating voltage is increased. Since operating voltage is controlled by RGB codes, it is essential that the user be able to estimate what color will be produced by any given code. This is the task of color estimation. Furthermore, it is desirable that the user also be able to estimate what RGB code will produce any particular color which has been assigned to a display region. This is the task of code selection. In other words, one would like to be able to take a given RGB code and estimate its Y, u', and v' parameters (color

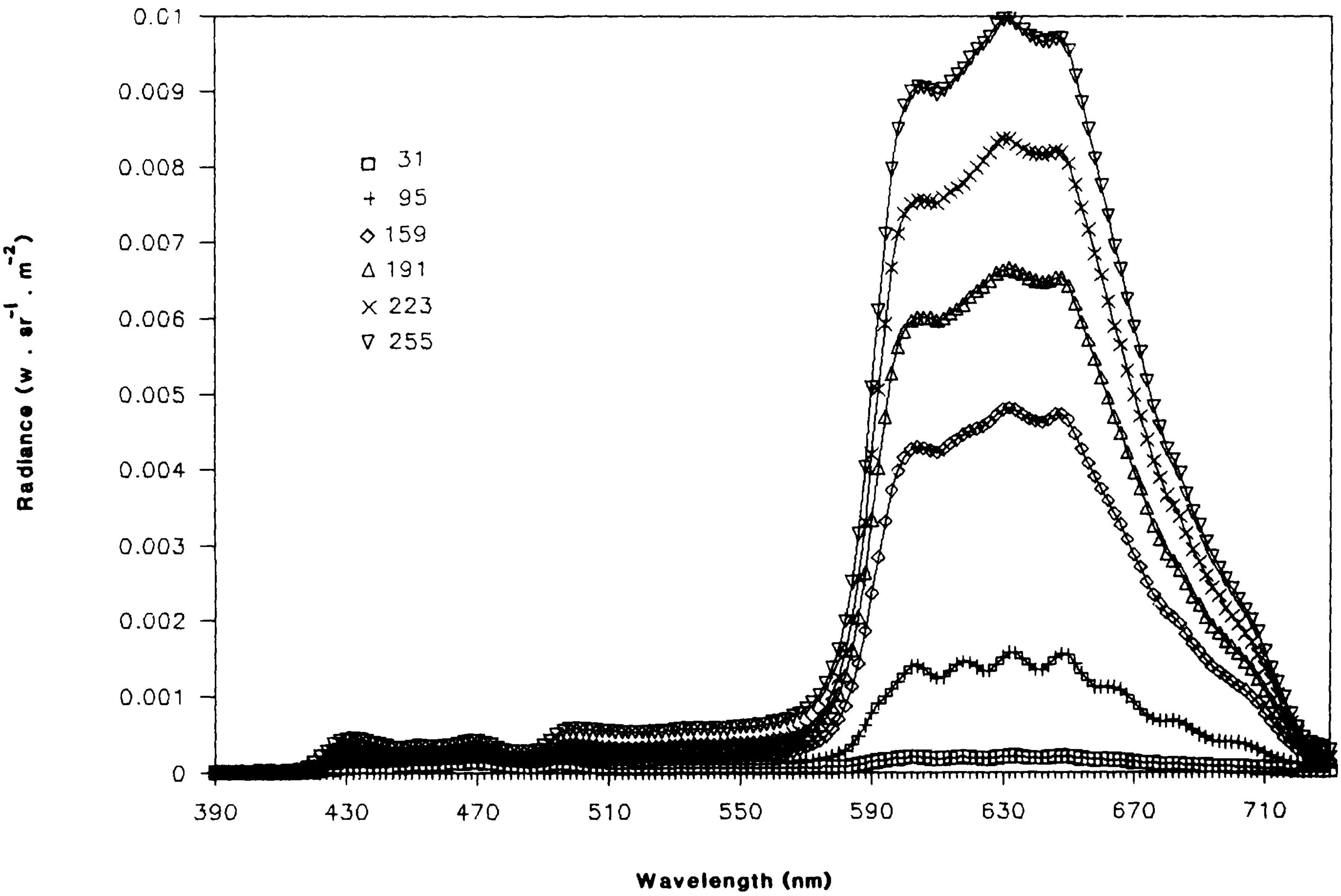


Figure 7. Spectral Energy Distribution of SLVP Red Primary. Measurements made on the HRL Talaria SLVP at 6 voltage levels corresponding to video levels 31, 95, 159, 191, 223, and 255.

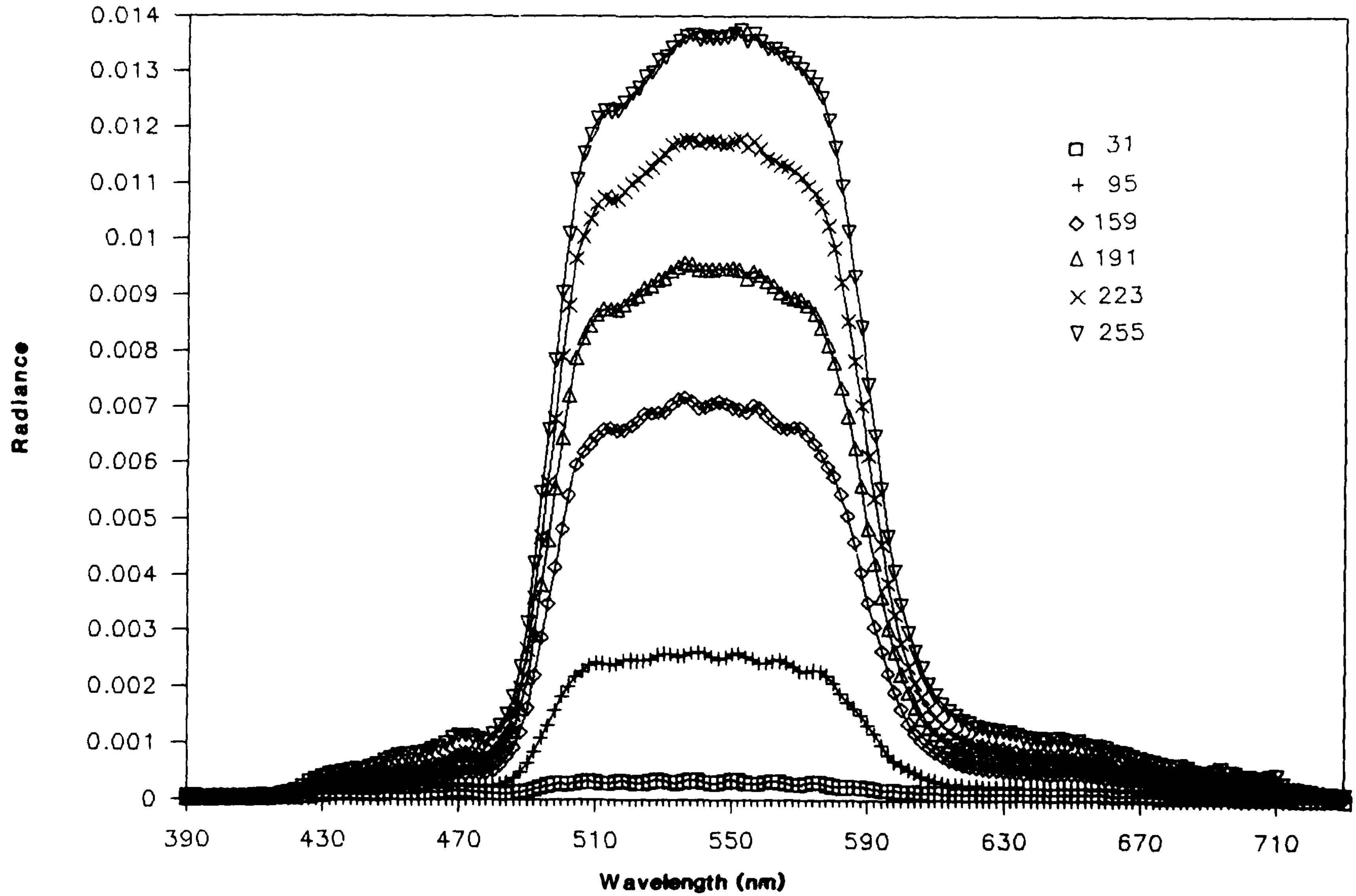


Figure 8. Spectral Energy Distribution of SLVP Green Primary.

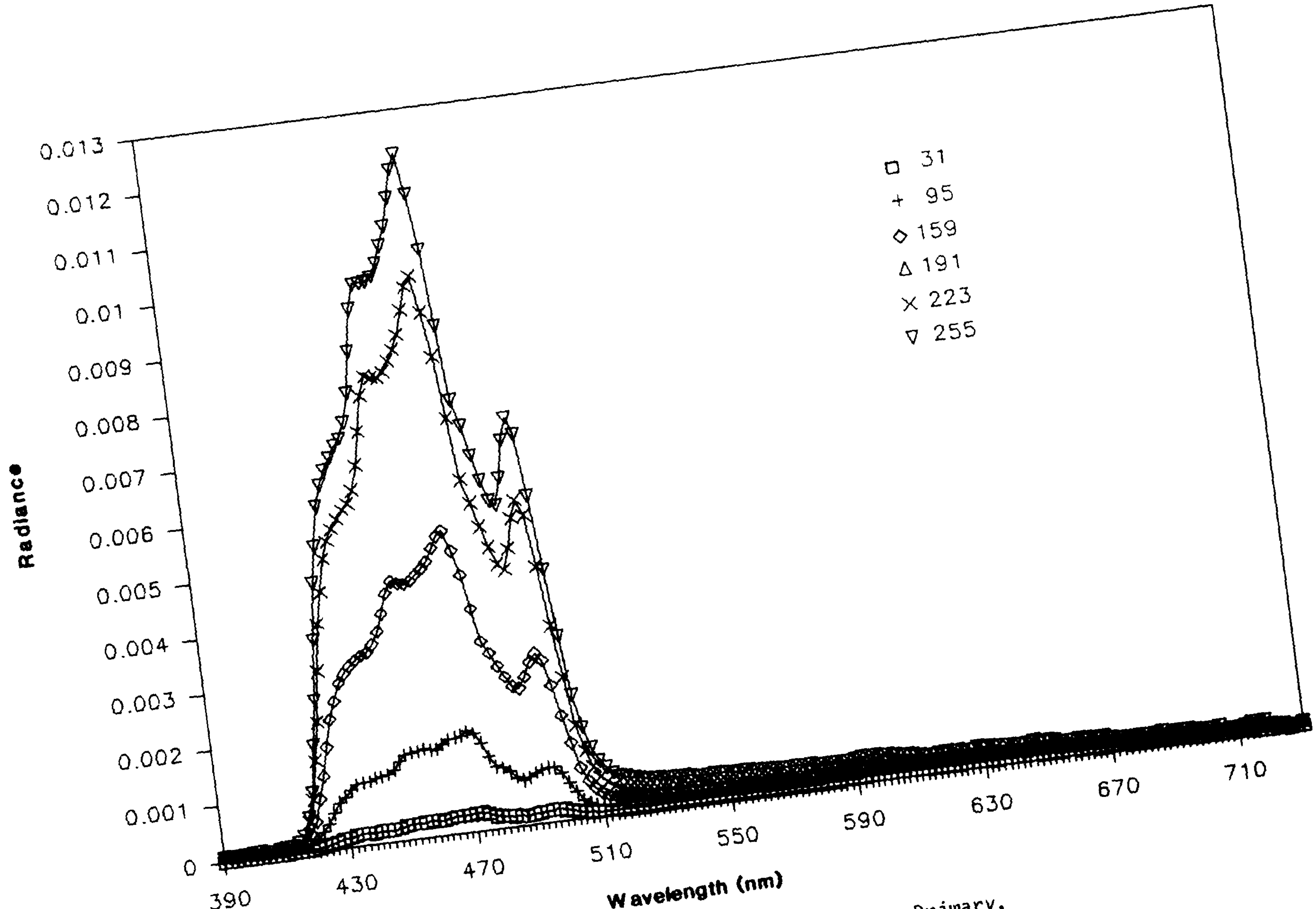


Figure 9. Spectral Energy Distribution of SLVP Blue Primary.

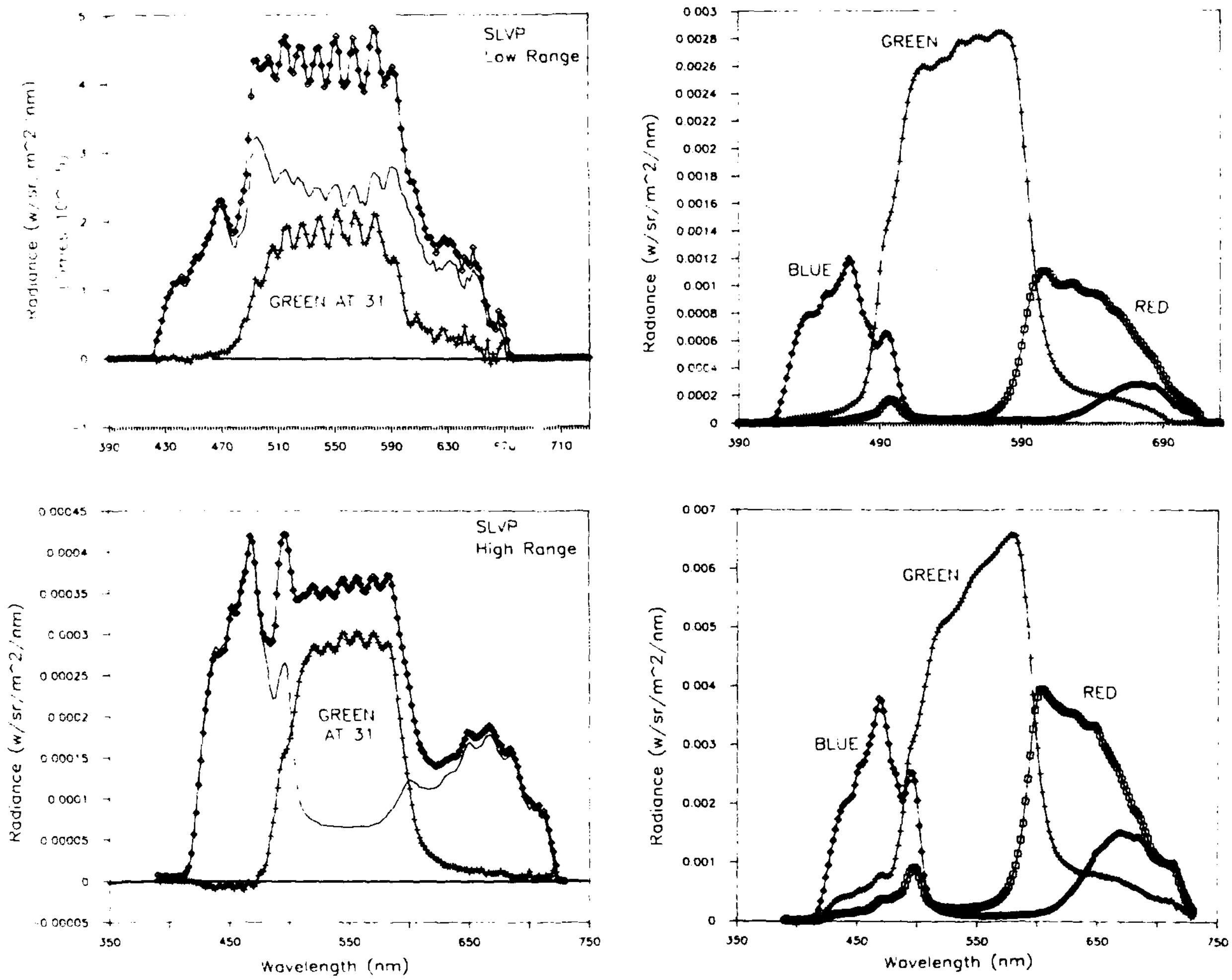


Figure 10. Spectral Energy Distributions of SLVP Primaries and Dark Field. Upper graphs are for an SLVP adjusted to give a maximum white of about 190 nits. Lower graphs are for the same SLVP adjusted to give 430 nits.

estimation). One would also like to be able to take a given color with specified Y, u', and v' parameters and estimate what RGB code will produce it on the intended device (code selection).

In order to fulfill these tasks, one must know the color parameters of the red, green and blue components which will be added together when a given digital code is used. If each primary has approximately constant u',v' coordinates at all 256 video levels, the additional information needed is merely the luminance Y for each primary at each level. Once this is known, color estimation and code selection will usually be relatively simple for a device which produces color by addition of three independent components.

The relation between video level and luminance (Y) is not linear for either the CRT or the LVP. This relation also differs from one device to another, even when the devices are identical in design. Therefore, it is necessary to obtain empirical data from each device in order to determine this function. The process of obtaining these empirical data is called calibration, and it is normally necessary to perform a calibration not only at the outset but also periodically while the device is in use. It is obviously also necessary to recalibrate whenever any new adjustment of its controls has been performed.

The SpectraScan radiometer has been used in all calibrations of AFHRL display devices. Each primary is measured at 32 equally spaced video levels, beginning at 7 and ending at 255. For example, when the red primary is being calibrated, successive RGB codes are 7,0,0; 15,0,0; 23,0,0; and so on up to 255,0,0. The dark field (RGB code 0,0,0) is also measured. Since October 1988, these measurements can be performed automatically at AFHRL by a computer program modeled on the CRT Colorimetry System developed in the Color Display Laboratory at the Armstrong Aerospace Medical Laboratory by Dr. David L. Post (Post, 1987).

Graphs of luminance as a function of video level are traditionally called "gamma functions" because such a function for most CRTs is a power function with a constant exponent called "gamma." Figure 11 shows data from two separate calibrations of the laboratory Talaria, compared with the gamma function for the red primary of a typical CRT. This CRT is a Hitachi Model CM2073A (which will be called "Hitachi A") on which calibration data were being collected in preparation for color appearance research. Its green and blue primary functions differ from the red function only in the scale on the luminance axis.

It is clear from Figure 11 that the shape of the functions for all LVP primaries is quite different from that of the CRT gamma function. Although there is a central region in which the luminance of all primaries varies almost linearly with operating level, the curve is positively accelerated at low levels and begins to show negative acceleration at high levels. Notice also that the two separate calibrations yielded different calibration curves, principally because the dark-field luminance was increased by adjustments made before the second calibration.

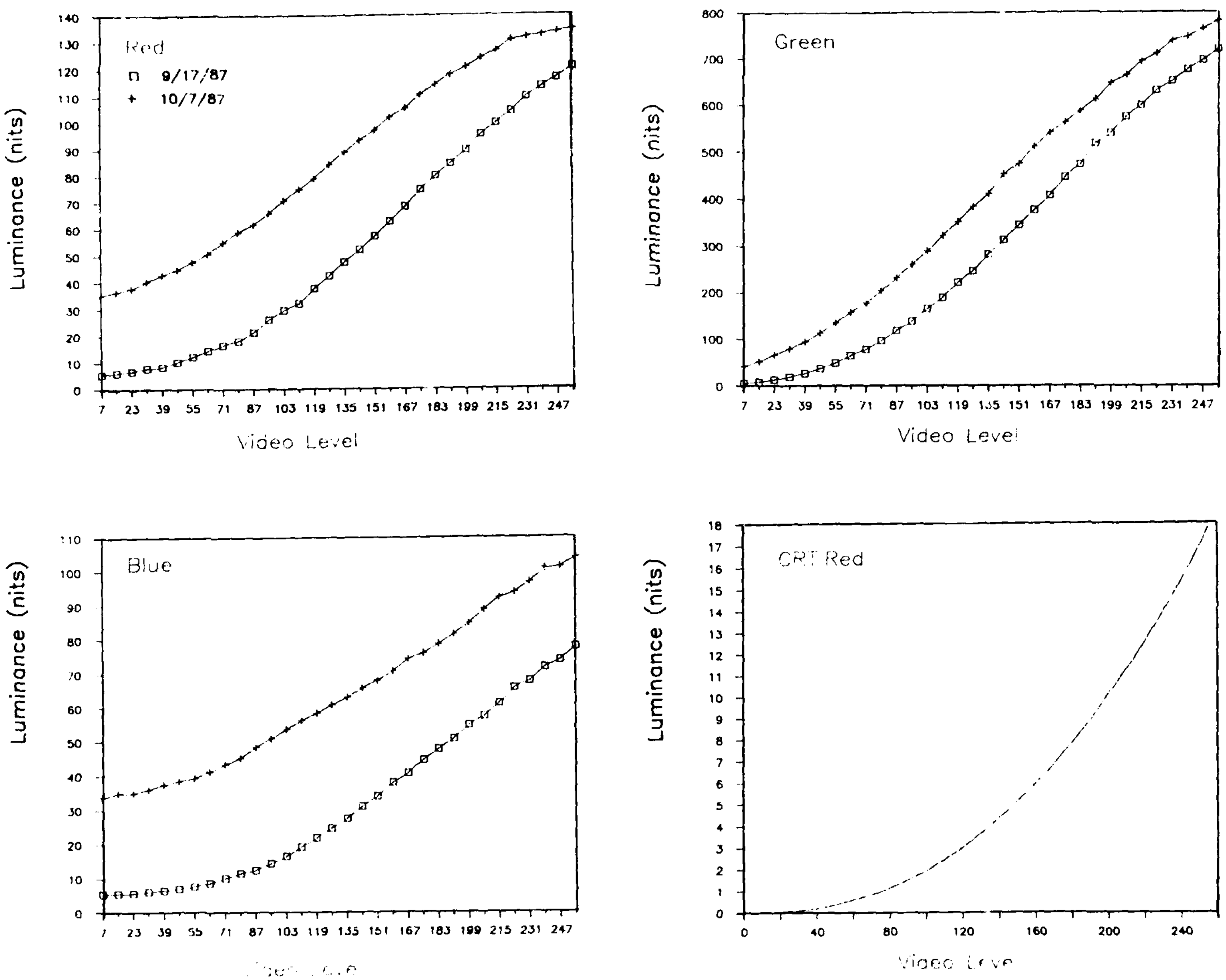


Figure 11. Luminance Output Functions for Talaria and a CRT. Two measurements are shown for each primary of Talaria. For comparison, the corresponding output function ("gamma function") for the red primary of the Hitachi A CRT is shown at bottom right. All curves are based on measurements at 32 equally spaced video levels.

In August 1987, a new General Electric Multiple Light-Valve Projector (MLVP) was installed for laboratory evaluation. The MLVP combines two light valves, one above the other, and each with its own xenon source; however, these two units share the same final optics. The upper light valve provides the green primary alone; its intensity is controlled by deflecting the green light through vertical slits. The lower light valve provides the red and blue primaries, gating the red light through horizontal slits and the blue light through vertical slits. Thus the red and blue primaries should be more nearly independent in the MLVP than in Talaria.

Figure 12 compares the calibration functions for SLVP and MLVP with those for a CRT (a Hitachi Model CM2086A35G, to be called "Hitachi B"). For Figure 12, the axes have been converted to logarithmic scales, and the dark-field component has been subtracted from all LVP data. Because the CRT functions are very close to power functions, they approximate straight lines in this log-log transformation (lower right). At the top of Figure 12 are log-log plots of MLVP luminance output in nits when it was adjusted to a very low luminance range (maximum about 195 nits) and when it was adjusted to a higher range (maximum about 650 nits). The higher range is designated "medium" because the MLVP can produce at least 1000 nits under these conditions. Several data points for the red primary were missed in this series of measurements, but the red function runs parallel to the blue function in this region.

Experience has shown that the LVP output functions, in a log-log plot, can be positively accelerated when the projector is adjusted for very low luminance output, as in the "low range" MLVP graph of Figure 12. They will be approximately linear when the projector is adjusted for somewhat greater luminance. The functions become negatively accelerated when the projector is adjusted for luminance near the limit of its capacity, as in the "high range" graph for SLVP at lower left in Figure 12.

Figures 11 and 12 have shown how video level affects the <u>luminance</u> of the primaries. The same calibration data can also be examined to learn whether operating voltage affects their <u>chromaticity</u>. Does the red light produced by digital code 31,0,0 have the same chromaticity coordinates as the red light produced at higher levels up to 255,0,0? Figure 13 shows the u',v' chromaticity coordinates for the SLVP when it was adjusted to the high range (430 nits). In the left graph the plotted points are the u'v' coordinates as measured (including the dark field). For the right graph, each point has been corrected by subtracting the dark-field XYZ tristimulus values and recalculating the u',v' coordinates. When this correction has been made, the u',v' coordinates of each primary have much greater constancy across the range of video levels, although there is still considerable variability for red and blue at the lowest levels.

Figure 14 shows similar plots for the two Hitachi CRTs. Hitachi A's primaries also do not have constant chromaticity at all video levels, and the amount of chromaticity change across the range of levels is quite similar to the amount of change in Figure 13. Hitachi B's primaries show much less variation in chromaticity.

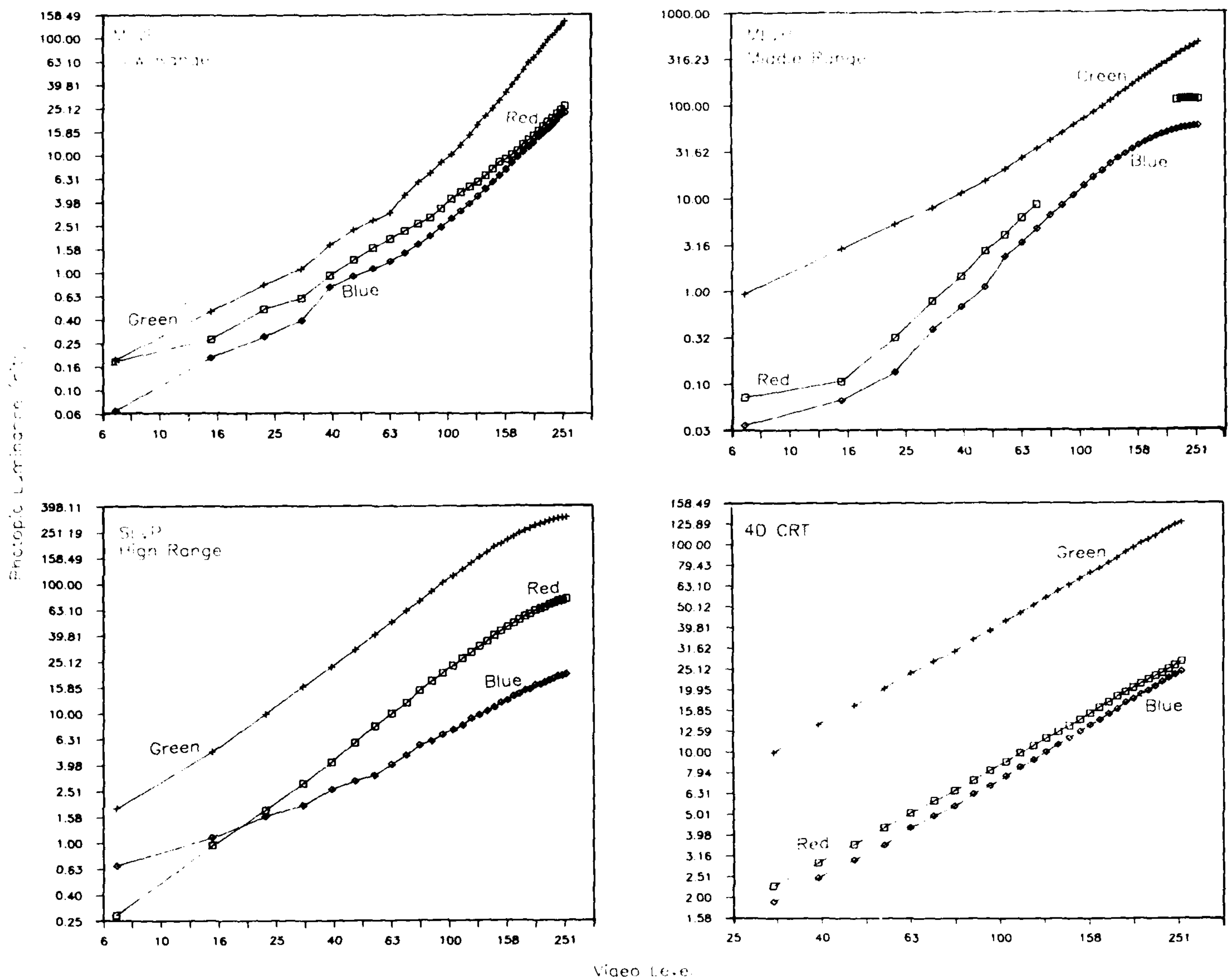


Figure 12. Luminance Output Functions Shown in Log-Log Plots. Top: MLVP at low (left) and medium ranges (right). Bottom: SLVP at high range (left); Hitachi A CRT (right).

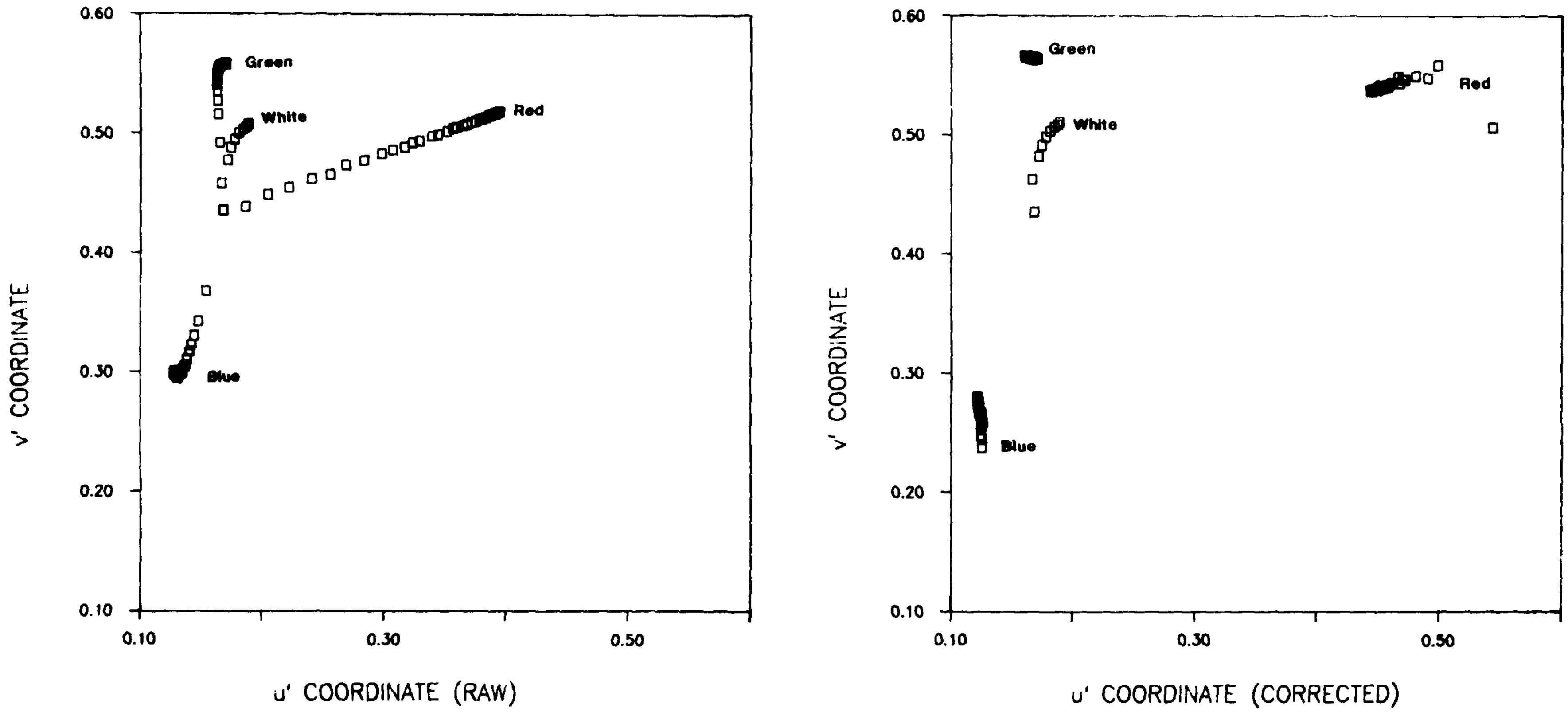


Figure 13. Variation in SLVP Chromaticity as a Function of Video Level. Left: chromaticities of red, green, and blue primaries uncorrected for dark field component start in the white region at video level 7 and increase in saturation toward the maximum at 255. Right: chromaticities corrected for dark field remain more nearly constant at all video levels.

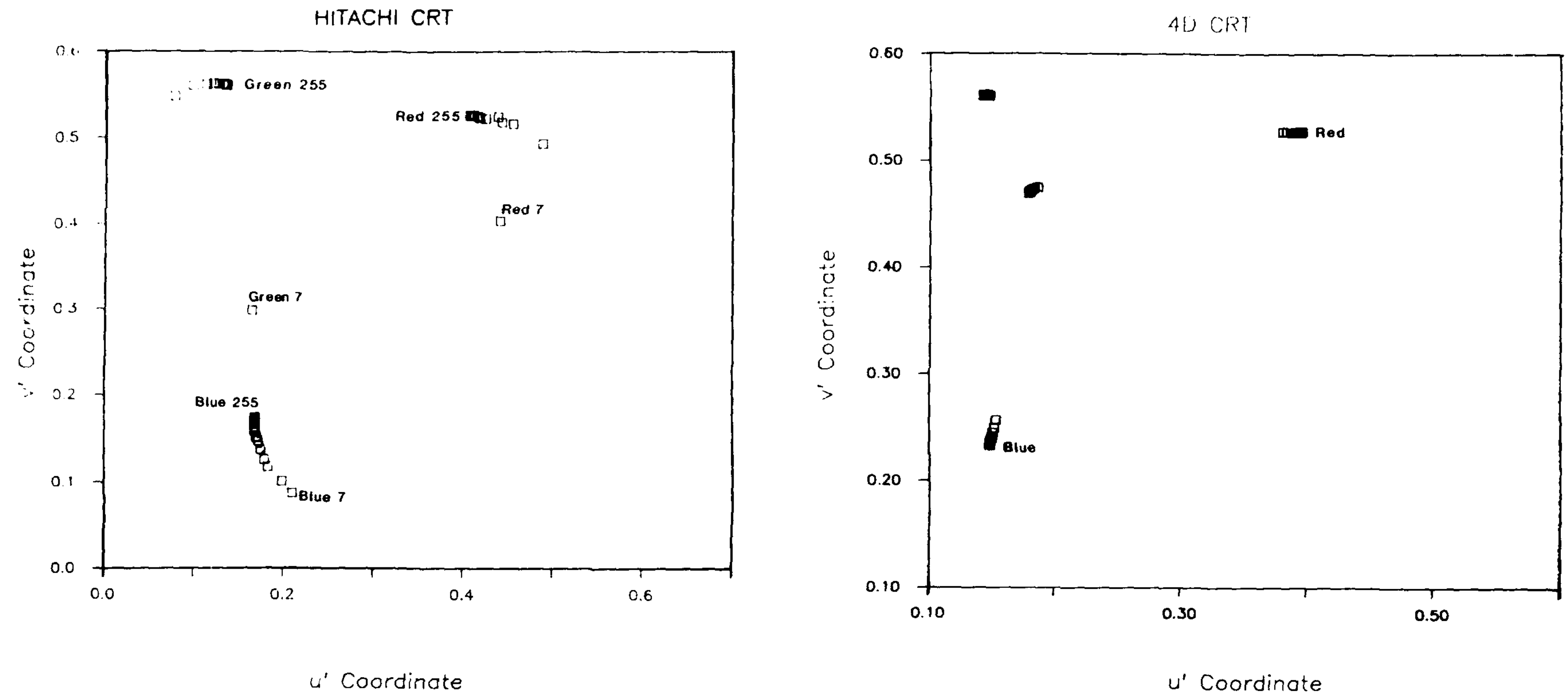


Figure 14. Variation in CRT Chromaticity Coordinates as a Function of Video Level. Chromaticities have been taken without correction from the calibration data on Hitachi A (left) and Hitachi B (right).

Finally, Figure 15 shows corrected u',v' coordinates for the MLVP primaries at eight video levels (31 to 255) for both the "low range" and the "medium range" studied. Each of these graphs shows the dark-field chromaticity point at the center. Although the dark-field chromaticity changed when the range was shifted from low to medium, the chromaticity of the three primaries remains the same when the dark-field correction has been applied.

Color Gamut of Single and Multiple Light-Valve Projectors

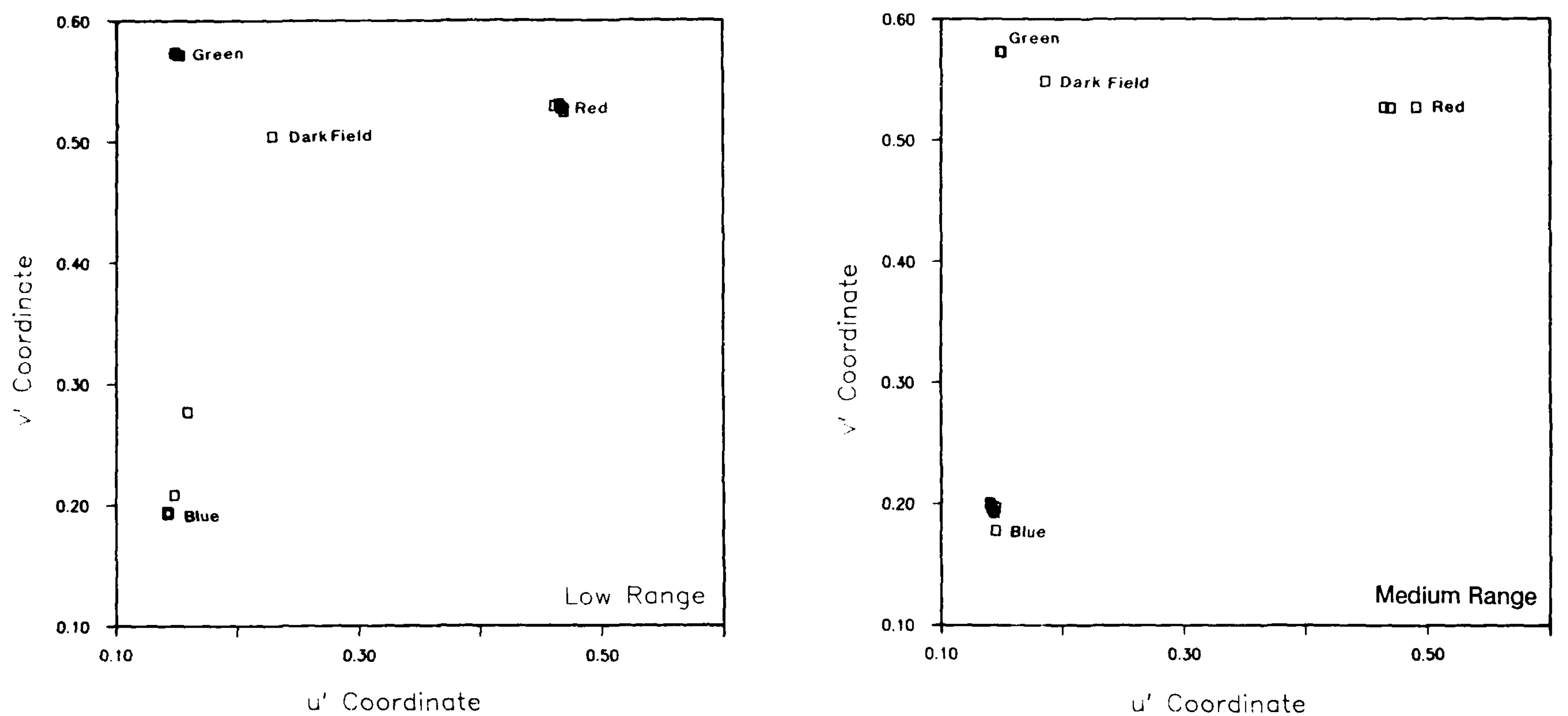
The range of colors available in a particular display is called the color gamut of that display. For any given luminance level, the color gamut can be plotted as a region in u',v' space.

When colors are achieved by the addition of three primaries, the color gamut must lie within the boundaries of a triangle whose apices are the u',v' coordinates of the individual primaries. With this set of primaries, it is impossible to achieve any color whose coordinates lie outside this triangle. However, at any particular luminance level, it is usually impossible to achieve all colors with coordinates inside the triangle. In general, the colors actually available will fill this triangle most fully at low luminances, and the gamut of obtainable colors will shrink markedly as the desired luminance level is increased.

Therefore, in order to describe the LVP's color gamut in meaningful terms, it is necessary to take luminance level into account. We can do so by using the concept of luminance factor, where a luminance factor of .80 corresponds to white and a luminance factor of .03 corresponds to black. In the Munsell Color System, variations in luminance factor correspond to variations along a dimension called value. By the use of published tables, colors described in terms of Y, u', and v' can be related to the Munsell system of color description (Wyszecki & Stiles, 1982, pp. 507-509, 840-852).

The four graphs in Figure 16 indicate the approximate extent of Talaria's color gamut at four levels of the dimension "value": value 3, corresponding to luminance factors near .12; value 5, near .20; value 7, near .40; and value 9, above .70. The letters R, G, B in these graphs represent the red, green, and blue primaries at maximum voltage. The remaining points are colors resulting from a sample of 512 digital code combinations chosen so as to explore the full range of possible combinations. All these colors were measured within a 5-day period, and the dark-field component was not removed since it is necessarily present in any color displayed by the LVP.

To draw these graphs, the luminances recorded for these 512 colors were first converted to relative luminances, using the principle that the brightest white in a reflected scene reflects about 80% of the incident illumination. Thus the maximum luminance obtained was given a relative luminance of .8 and all other luminances were converted to the same relative scale. Then those points with relative luminance between .09 and .149 were plotted in Figure 16, top left, to show the gamut near Munsell value 3. Those with relative luminance between .15 and .25 (near Munsell value 5) appear at top right, those with relative luminance between .30 and .50 (Munsell value 7) at bottom left, and those with relative luminance above .70 (Munsell value 9) at bottom right.



<u>Figure 15.</u> Variation in MLVP Chromaticity as a Function of Video Level. Left: corrected chromaticities of red, green, and blue primaries when the MLVP was adjusted to the "low range." Right: corrected chromaticities when adjusted to the "medium range."

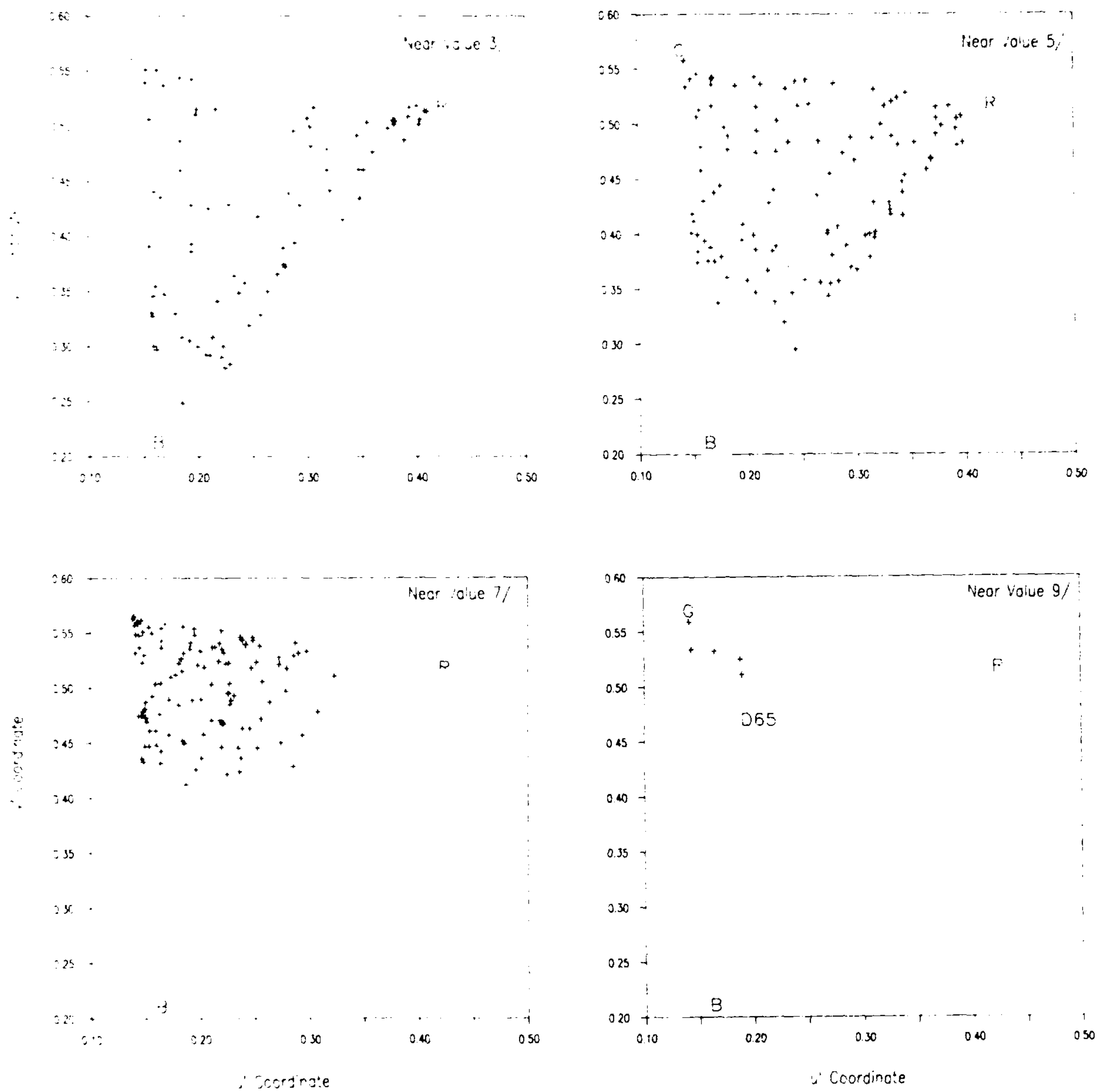


Figure 16. Color Gamut of Talaria at Four Levels of Luminance Factor. Points are from a sample of 512 RGB combinations; letters R, G, B, and D65 represent chromaticity coordinates of the red, green, and blue primaries and of D65 daylight. Top left: near Munsell Value 3/ (luminance factor approximately .12); top right: near Munsell Value 5/ (luminance factor approximately .20); bottom left: near Munsell Value 7/ (luminance factor approximately .40); bottom right: near Munsell Value 9/ (luminance factor .70 and above).

Figure 16 shows that the greatest range of colors within the triangle bounded by the primaries' u',v' values is obtained at a low relative luminance (near .12). Even at luminance factor .20 (Munsell value 5), the gamut has already shrunk in the region near the blue primary; this loss of possible colors near blue reflects the relatively weak light output of the blue primary. When a luminance factor of .40 is required, the gamut fails to include reds and purples as well as blues. At the highest luminance factor, which normally corresponds to neutral white, the only available colors in the gamut are displaced away from the location of the recommended reference white, D65 (u' = .20, v' = .47). In the presence of a bright D65 white, the colors at this highest luminance factor would appear distinctly green.

These variations in color gamut with luminance level should not be regarded as a limitation of light valves, nor indeed as a disadvantage in simulating natural scenes, since reds and blues in natural scenes are also dim relative to yellows and whites. It is also not inevitable that the maximum white of a light valve will lie in the green. The SLVP being studied late in 1988 showed a maximum white much closer to D65.

The relations between color gamut and luminance factor reflect the influence of the <u>gun balance coefficients</u> chosen for the LVP. Table 5 compares the gun balance coefficients for the Talaria display with those of the major AFHRL simulator displays and with the Hitachi A CRT. For both CRT and Talaria, over 60% of the total light output is provided by the green primary, and the red primary provides at least twice as much light as the blue primary. The choice of gun balance coefficients is dictated largely by the luminous efficacy function for daylight vision, shown in Figure 1, which is characterized by maximum sensitivity in the medium wavelength region, rather less sensitivity to longer wavelengths, and least sensitivity to short wavelengths below 500 nm.

<u>Table 5.</u> Gun Balance Coefficients of AFHRL Displays

Primary	Display device				
	Talaria	Hitachi A CRT	Dome AOI	Dome background	Dodec
Red	0.28	....0.24	0.19	0.15	0.16
Green	0.61	....0.64	0.67	0.73	0.67
Blue	0.11	....0.12	0.14	0.12	0.17

It is clear from this table that the relative predominance of green is greater in the simulator displays than in the Talaria itself, and that the dominance of the red over the blue primary also decreases markedly in the simulator displays. Thus, it can be expected that the maximum luminance

white for simulator displays will deviate from D65 in the green direction. Data confirming this deviation have already been presented in connection with the Scene Color Study in Section II, where the neutral (black, gray, white) areas all showed color shifts away from the neutral region in color space with the high luminance neutrals moving toward green.

Will this shift be perceived as a color distortion? Probably not, since color appearance studies indicate that the brightest area in a natural scene will be perceived as white even when its chromaticity deviates toward yellow or blue (Bartleson, 1979). However, when a yellowish region is accepted as white, the appearance of neighboring regions of color space is correspondingly modified. If this rule also holds when a greenish region is accepted as white, such modifications in color appearance need to be anticipated and taken into account when designing the color-rendering procedure to be used.

Additivity and Independence of Primaries

Suppose that we have measured Y, u' and v' for each of three CRT primaries at each of the 32 video levels mentioned above. If the three primaries do not interact with each other when they operate simultaneously, then the light output from RGB code 223,223,223 should be simply the sum of the outputs of red alone at 223, green alone at 223, and blue alone at 223. We can check whether this is so, if we replace u' and v' with the linearly related statistics X and Z, and take the three parameters X, Y, and Z for each of the three primaries. Thus,

Primary (digital code)	X	Y	Z	
Red (223)	36.8	22.0	3.08	
Green (223)	34.8	58.3	9.30	
Blue (223)	15.9	10.9	79.40	
Sum of all three:	87.5	91.2	91.8	u' = .2021 v' = .4742
Actual measured X,Y,Z values:	85.3	90.0	91.8	u' = .1995 v' = .4734

The actual measured values are very close to those estimated from additive combination of the primaries. To evaluate how close the estimate is, two statistics may be calculated as follows: (a) proportional error in luminance, calculated by the equation

$$Y \text{ error} = (\text{Estimated } Y - \text{Measured } Y)/\text{Measured } Y \qquad (1)$$

and (b) the distance between the estimated and actual u',v' points in color space, calculated by the equation

$$\text{distance} = \sqrt{(u'_{est} - u'_{meas})^2 + (v'_{est} - v'_{meas})^2} \qquad (2)$$

In this example, the Y error is .013, or 1.3% of the actual measured value; the error in chromaticity is a distance of .0028 in uniform chromaticity space.

The data used in the above example were obtained from the Hitachi A CRT. The following example shows how these calculations should be made for the LVP. Since each calibration measurement has included the dark-field component, this component has to be removed from each measurement in order to obtain the XYZ tristimulus values attributable to red, green or blue alone. Then the output produced by RGB code 223,223,223 will also include the dark field as a fourth component:

Component	X	Y	Z	
Red (223)	183.7	98.0	13.14	
Green (223)	383.0	678.2	74.73	
Blue (223)	107.0	61.2	578.94	
Dark Field	29.4	32.7	18.02	
Sum of all four:	703.1	870.1	684.83	u' = .1779 v' = .4953
Actual measured X,Y,Z values:	562.2	769.3	388.56	u' = .1695 v' = .5219

In this LVP example, the Y error is 0.13, or 13 percent of the actual measured value. The error in chromaticity is a distance of .0279 in uniform chromaticity space.

The error in LVP calculations is not always this large. These examples have been taken from two lines of Table 6, which compares CRT and LVP data on eight RGB combinations in which red, green and blue are all at the same video level (31, 63,...,255). Part 1 of the table shows data from the Hitachi A CRT; Part 2 shows parallel data from the Talaria. The left-hand side of each table shows the X, Y, and Z values obtained from each of these eight measured RGB combinations, followed by the u' and v' coordinates corresponding to these tristimulus values. The middle portion of the table shows the X, Y, and Z values predicted from additive combination of those values measured with each primary alone, followed by the corresponding u' and v' values. The two right-hand columns in each part of the table summarize the errors made in this prediction.

It is clear from Table 6 that most of the CRT colors can be very accurately predicted from addition of primary tristimulus values. The estimates for LVP colors are somewhat less precise. The estimated LVP luminances are as much as 14% too high, and these errors increase as video level increases. At the higher video levels, the distance between estimated and actual chromaticity points is about 10 times as great as with the CRT.

Calculations of the sort shown in Table 6 are often used to determine whether the three primaries are <u>independent</u> of each other. If the output of one primary depends to any significant degree on the video level of one

Table 6. Additivity Data Comparing Hitachi A CRT and Talaria

White level	Measured tristimulus values X	Y	Z	Coordinates u'	v'	R+G+B tristimulus values X	Y	Z	Coordinates u'	v'	Y Error	u'v' Error
Part 1. CRT Data												
31	2.79	2.85	2.60	.2091	.4809	3.61	3.61	3.29	.2134	.4804	0.270	.0043
63	7.96	8.24	7.92	.2049	.4775	8.43	8.60	8.29	.2077	.4769	0.043	.0029
95	16.16	16.87	16.56	.2027	.4761	16.97	17.64	17.06	.2041	.4771	0.046	.0016
127	29.19	30.57	30.70	.2014	.4745	29.82	31.15	30.88	.2022	.4754	0.019	.0013
159	43.49	45.62	46.68	.2005	.4731	45.16	47.13	47.51	.2019	.4741	0.033	.0018
191	65.85	69.21	71.14	.1999	.4728	67.77	70.68	72.42	.2015	.4729	0.021	.0016
223	85.29	89.97	91.84	.1995	.4734	87.44	91.18	91.81	.2021	.4742	0.013	.0027
255	118.10	123.92	128.83	.1999	.4719	121.36	126.08	128.32	.2025	.4733	0.017	.0029
Part 2. Light-Valve Data (corrected for dark field)												
31	74.91	90.27	51.36	.1893	.5132	74.57	90.59	52.40	.1875	.5126	0.0036	.0019
63	145.67	181.26	108.94	.1826	.5112	148.54	184.82	118.18	.1814	.5078	0.0196	.0036
95	237.81	302.01	183.60	.1788	.5110	252.49	312.89	218.98	.1803	.5026	0.0360	.0085
126	338.09	436.63	259.78	.1764	.5126	374.33	464.02	338.09	.1793	.5002	0.0627	.0127
159	433.33	571.70	322.98	.1737	.5157	497.76	618.91	463.22	.1782	.4986	0.0826	.0177
191	504.15	679.26	363.48	.1711	.5188	602.81	745.54	577.08	.1784	.4964	0.0976	.0236
223	562.20	769.33	388.56	.1695	.5219	703.14	870.09	684.83	.1779	.4953	0.1310	.0279
255	605.14	836.51	389.89	.1690	.5256	766.74	955.13	773.86	.1761	.4936	0.1418	.0328

or both of the other primaries, then obviously one would not be able to estimate the color output simply by adding the values obtained when only one primary is operating at a time. From the CRT data in Table 6, one would judge that the CRT primaries are independent of each other.

On the other hand, the data of Table 6 leave some doubt about the independence of Talaria's primaries. Is it possible that the LVP primaries are actually interdependent, so that the output of each primary is influenced in some way by the video levels of the other primaries acting at the same time? In order to answer this question directly, three additional experiments were performed.

In the first experiment, green was kept at zero, and red and blue combinations were studied. While red was held constant at video level 31, blue was stepped through levels 31, 63, 95, 127, 159, 191, 223, and 255, and both luminance and chromaticity were recorded. This procedure was repeated with red constant at five additional levels (127, 159, 191, 223, and 255). The resulting luminance functions are shown in Figure 17 (top). Despite some irregularities, the general shape of the function describing changes in red/blue output remains the same at all levels of red output. This graph does not indicate that the video level of red significantly affected the output of blue.

The same data, augmented with additional points for red at video levels 63 and 95, are plotted in the lower part of Figure 17, describing the luminance of the RB combinations as the red video level varies while blue is held constant at each of 6 video levels. Again, the shape of the function does not vary as a result of changes in the blue video level.

Thus, these data on RB combinations do not support the idea that red and blue influence each other's output. From the functions shown in Figure 17, one would conclude that there is little or no interdependence between the red and blue primaries. In spite of their technological relationship in the Talaria's design--which requires that both red and blue be controlled by diffraction patterns affecting the same direction of deviation--the results of this experiment suggest that red and blue are, indeed, essentially independent of each other.

A second and similar experiment was performed to test the interaction of red and green while blue remained at zero. Figure 18 (bottom) shows how the output varied with red video level; each function represents the total luminance output as a function of red video level, with the video level of green differing from one function to another. Because of the great difference in gun balance coefficients, the changes in red video level make relatively little difference in total output. Nevertheless, the six curves are closely parallel, indicating that the green video level does not appreciably change the shape of the output function.

Figure 18 (top) shows the curves for different constant levels of red. The curves here show the effect of varying the video level of green, and they are not only all similar to each other, but they are all very similar to the overall shape of the calibration curve (Figure 11) shown earlier for the green primary alone.

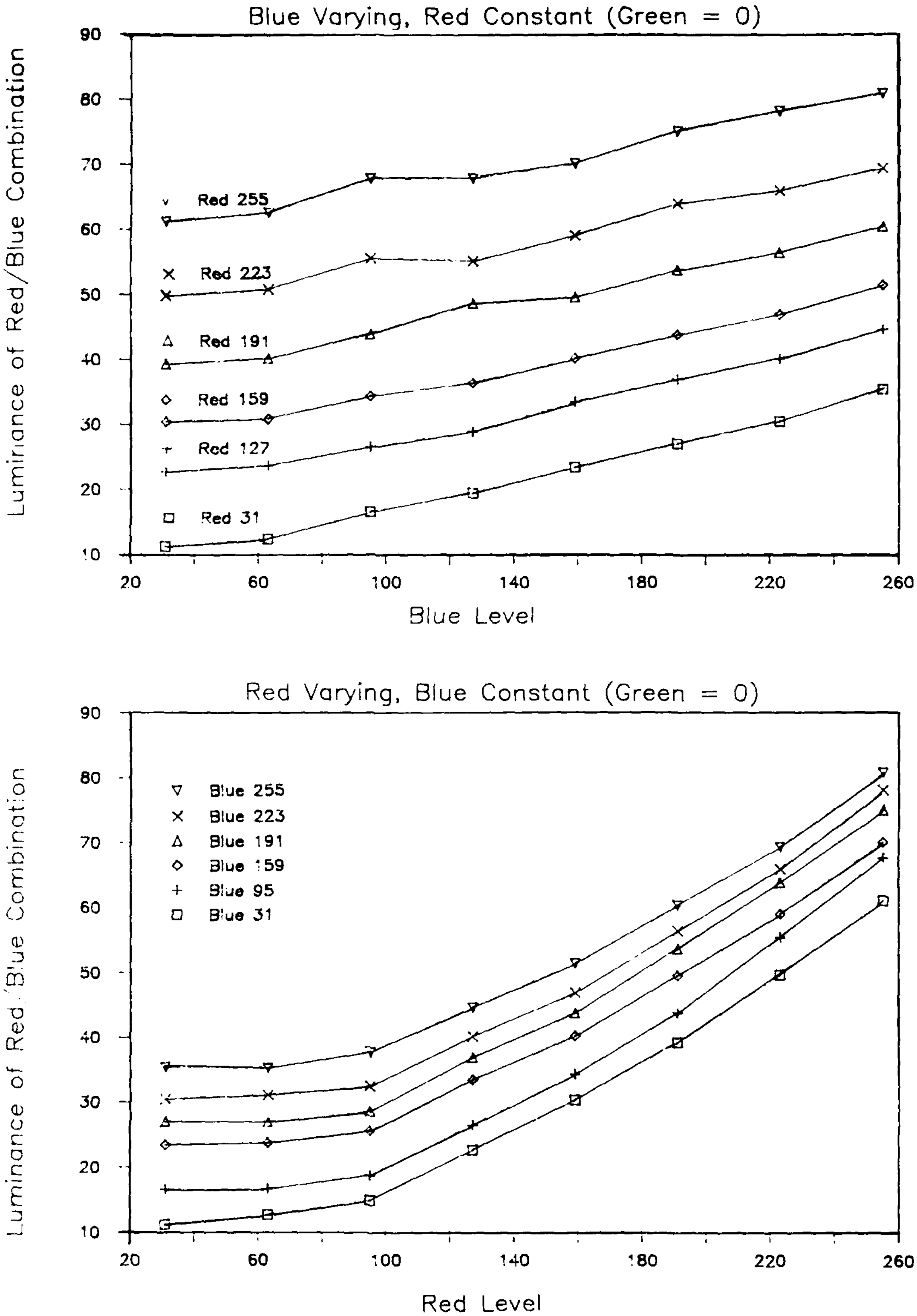


Figure 17. Talaria Test for Red/Blue Independence. Top: luminance output as a function of blue video level; separate curves are for different video levels of the red primary. Bottom: luminance output as a function of red video level; separate curves are for different video levels of the blue primary. Measurements made in June 1987; green primary at zero for all curves.

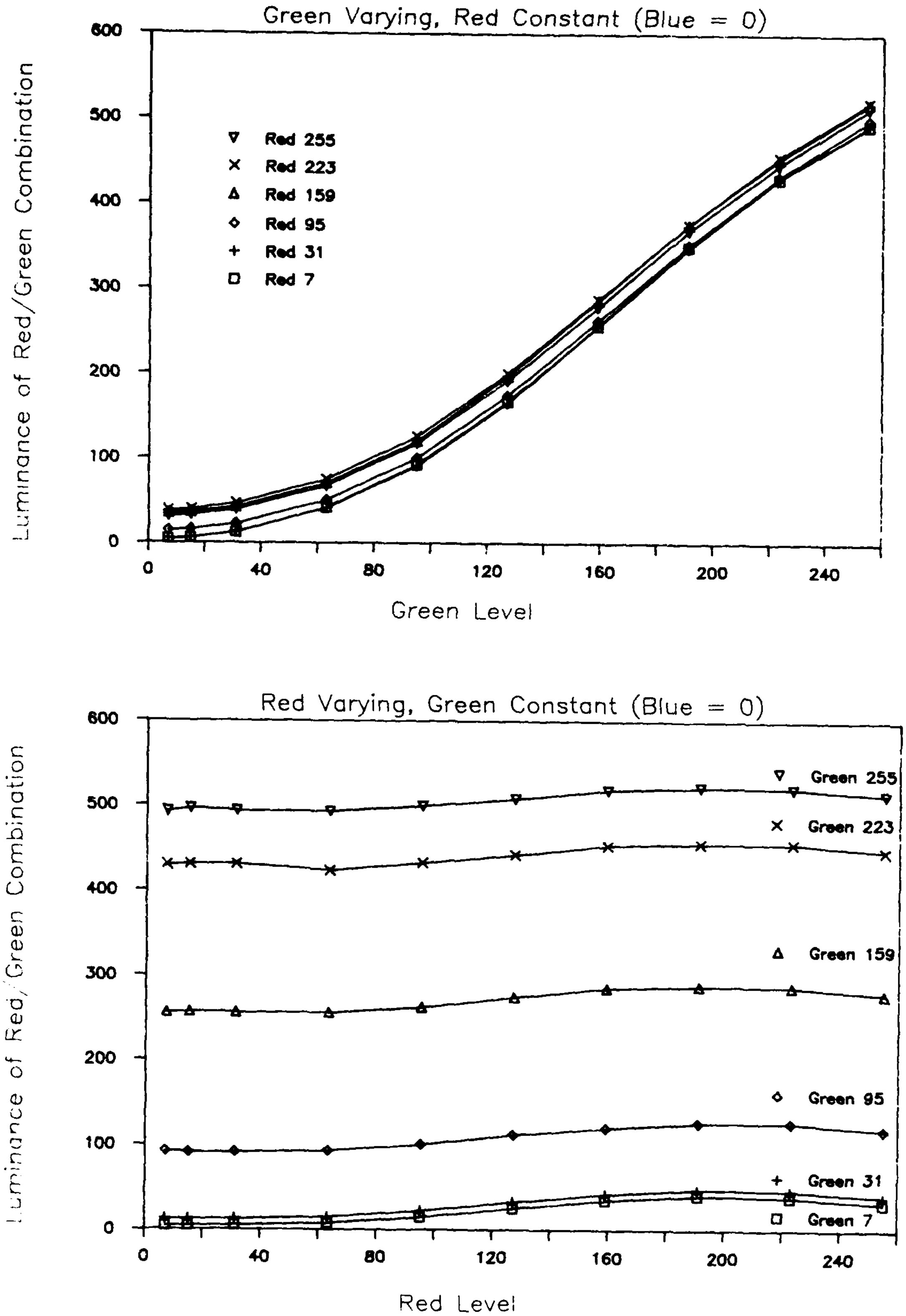


Figure 18. Talaria Test for Red/Green Independence. Top: luminance output as a function of green video level; separate curves are for different video levels of the red primary. Bottom: luminance output as a function of red video level; separate curves are for different video levels of the green primary. Measurements made in December 1987; blue primary at zero for all curves.

This RG experiment was repeated with the third (blue) primary at two non-zero levels (127 and 223). Although the resulting graphs lie somewhat higher on the luminance axis than those in Figure 18, because of the additional light provided by a non-zero blue primary, their shape is the same as when blue was absent from the mixture. Even when all three primaries are operating at a non-zero level, there is no evidence for interaction of the primaries.

From these experiments, it can be concluded that the difficulty encountered in estimating LVP display color from the addition of primaries is not due in any major way to actual interaction or interdependence of these primaries. However, a third experiment shows that a slight interaction between red and blue is indeed present.

At the suggestion of Tom True (personal communication), the red/blue experiment was repeated, and luminance output was measured through red or blue filters. Figure 19 shows the results when red was held constant at video level 31 or 255 and blue was stepped through 8 video levels. Squares indicate total red/blue output measured with no filter in place. Diamonds indicate total output measured through a blue filter; as blue video level increases, output in the blue region increases as expected. However, the output measured through a red filter, shown by crosses, remained constant with increases in blue video level when red was at 31 but decreased when red was at its maximum 255. Thus, red output could not be maintained at its maximum level as blue increased; increases in blue did in fact add output in the blue region at the expense of output in the red region of the spectrum.

IV. COLOR CONTROL REQUIREMENTS

Control of display color implies ability to estimate or predict the colors which will result from a given RGB code and ability to calculate the RGB code which will produce light output having a specified luminance and chromaticity. These are the tasks of color estimation and code selection, first discussed in Section III, page 18. The following section will discuss these tasks in greater detail.

Color Estimation by Matrix Multiplication

It has already been shown that the colors which will result from a given RGB code may be estimated by addition of the primary X, Y, and Z values. It has also been shown that the dark-field tristimulus values must be included when the display device is an LVP. In practice, one rarely uses such direct addition of primary XYZ values, since there is a more powerful method which is based on the same assumptions of additivity and independence. This method employs matrix multiplication.

The matrix multiplication method requires luminance-output functions for each primary plus information about the chromaticity of each primary. It is ordinarily assumed that this chromaticity does not vary much with luminance level. Values of the x, y, and z chromaticity coordinates (see Appendix A for the defining equations in terms of X, Y, and Z tristimulus

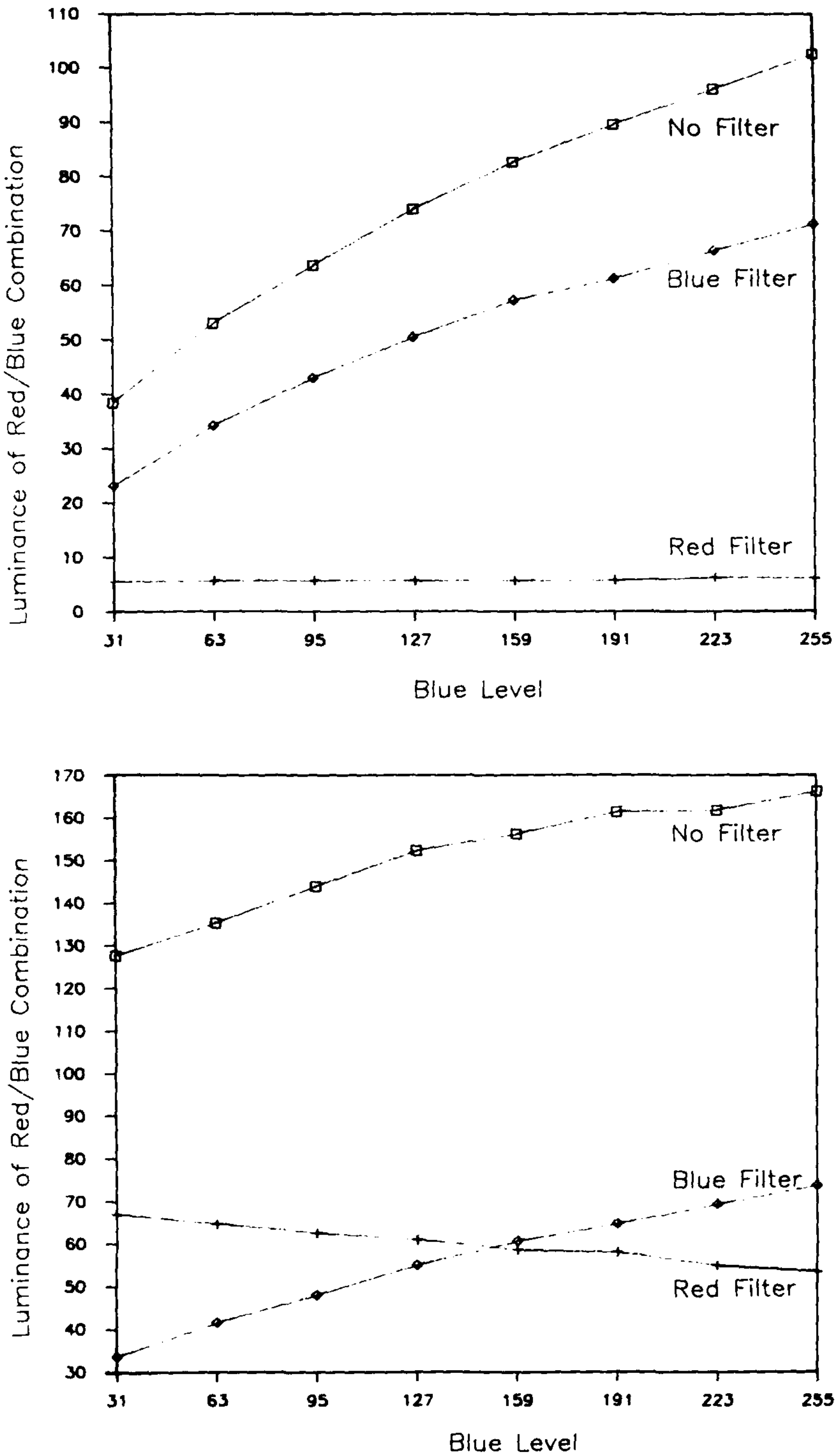


Figure 19. Independence Test with Red and Blue Filters. SLVP output measured with no filter and with either a red or a blue filter between the PR703A and the screen. Top: red at video level 31; bottom: red at video level 255. Green primary at zero througnout. Measurements of combined red/blue output show loss of output in the red region as blue video level is increased, but only when red is at the higher video level.

values) are entered into a 3 x 3 matrix as follows. Letting x_R represent the x-coordinate for the red primary and using the same convention for the other eight coordinates, the matrix M is defined as

$$M = \begin{vmatrix} x_R & x_G & x_B \\ y_R & y_G & y_B \\ z_R & z_G & z_B \end{vmatrix} \tag{3}$$

A more convenient form of the matrix is obtained when each element is divided by its corresponding y-coordinate. Thus,

$$M_P = \begin{vmatrix} x_R/y_R & x_G/y_G & x_B/y_B \\ 1 & 1 & 1 \\ z_R/y_R & z_G/y_G & z_B/y_B \end{vmatrix} \tag{4}$$

This form of the chromaticity matrix for a given display permits estimation of the tristimulus values X, Y, and Z for the color which will result when some designated RGB code is applied to a display area:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = M_P \begin{pmatrix} Y_R \\ Y_G \\ Y_B \end{pmatrix} \tag{5}$$

where Y_R represents the luminance in nits of the red primary at the video level it is to have in the combination, and Y_G and Y_B represent the corresponding luminances of the green and blue primaries at their respective levels. To estimate X, Y, and Z from RGB code 159,95,127, for example, we would need only (a) the chromaticity matrix, determined by measurements made at or near the maximum video level for each primary; and (b) a calibration curve for each primary, such as those given in Figure 11. It is sometimes suggested that a mathematical function be fit to the calibration curve in order to calculate luminance values lying between the actually measured luminances. However, in almost all cases, more accurate results will be obtained by using piecewise linear interpolation (Post & Calhoun, 1987).

Use of this matrix method will provide a good approximation to the actual luminance and chromaticity which can be achieved by various RGB combinations on a CRT. It can also be applied to the LVP, provided the dark-field component is taken into consideration. For an LVP, equation (5) yields only the tristimulus values which will be contributed by the red, green, and blue primaries in response to a given RGB code. However, the response of the LVP will include the additional dark-field component. To obtain the tristimulus values of the actual color output in response to an RGB code, the XYZ values of the dark field must be <u>added to</u> the XYZ vector derived from equation (5). To make this difference clear, equation (5) may be rewritten for the LVP as follows:

$$\begin{pmatrix} X_S \\ Y_S \\ Z_S \end{pmatrix} = M_P \begin{pmatrix} Y_R \\ Y_G \\ Y_B \end{pmatrix} \tag{6}$$

In equation (6), X_S, Y_S, and Z_S represent the XYZ values resulting from the RGB signal component of the color. To calculate XYZ values for the color which will actually be observed, the dark-field XYZ values (X_D, Y_D, Z_D) must be added: $X = X_S + X_D$, $Y = Y_S + Y_D$, and $Z = Z_S + Z_D$. The values of Y_R, Y_G, and Y_B are, of course, obtained from the calibration measurements after they have been corrected for the dark-field contribution. Table 7 shows the results obtained when equation (6) was used to predict the color response of an MLVP to a set of 19 RGB codes sampled from an AFHRL data base.

Since the matrix method uses all the information about primary luminances which the calibration contained, estimation of luminance (Y) is just as accurate by this method as by direct primary addition. However, the estimates of u' and v' are not as accurate. The matrix method uses only a small part of the calibration information about primary X and Z values; it uses only those X and Z values at video level 255 to calculate the chromaticity coordinates x, y, and z for each primary. All the other X and Z values are dropped from the calculation. If chromaticity does not vary much with video level, little information will have been lost, and the matrix method will be nearly as accurate as direct addition of primary XYZ values.

In the Table 7 example, the u',v' error varies between .0061 and .0288 when the matrix method is used. If the primary XYZs had been directly added (as they were in Table 6), the u',v' error would range between .0008 and .0057. This large difference in accuracy indicates that chromaticity of the MLVP primaries did vary considerably from one video level to another, so that a large amount of essential information was lost by using X and Z values from only one video level.

Code Selection for CRTs and LVPs

When the matrix equation accurately describes the relation between tristimulus values and primary luminances, it is not difficult to select an RGB code that will produce a color specified in terms of Y, u', and v' values. Given that X, Y, and Z can be directly calculated from Y, u', and v' (see Appendix A), equation (5) can be inverted to give the relation

$$\begin{pmatrix} Y_R \\ Y_G \\ Y_B \end{pmatrix} = M_P^{-1} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \tag{7}$$

Again, Y_R represents the luminance which the red primary must have in order to produce a color with tristimulus values X, Y, and Z; and Y_G and Y_B represent the luminances required from the green and blue primaries. The term M_P^{-1} denotes the inverse of the matrix M_P. Once the values of Y_R, Y_G, and Y_B have been calculated by equation (7), the calibration data for the red, green, and blue primaries can be used to select RGB codes which will produce these luminances.

Equation (7) can be applied for CRTs with no ambient illumination. For LVPs, it must be modified to incorporate the dark field. The equation for LVPs may be written as follows:

Table 7. Color Estimation for 19 RGB Codes Applied to MLVP Display

Index No.	RGB code	Measured values Y(nits)	Measured values u'	Measured values v'	Predicted values Y(nits)	Predicted values u'	Predicted values v'	Error of prediction Y (%)	Error of prediction u',v' Dist.
26	10,10,200	25.67	.1515	.2301	25.73	.1568	.2573	0.25	0.0278
30	200,100,16	37.62	.3510	.5311	38.03	.3264	.5305	1.09	0.0246
40	200,16,16	29.85	.4018	.5203	29.11	.3752	.5195	-2.48	0.0266
42	100,100,150	27.66	.1795	.3322	29.26	.1828	.3608	5.79	0.0288
46	16,65,20	10.07	.1890	.5144	10.03	.1924	.5195	-0.37	0.0061
62	180,13,96	27.27	.3250	.4342	28.07	.3113	.4436	2.94	0.0166
64	10,63,72	11.80	.1761	.4154	11.53	.1804	.4279	-2.27	0.0132
84	136,164,158	58.67	.1855	.4148	63.16	.1878	.4353	7.66	0.0206
102	100,50,16	12.15	.2729	.5162	12.23	.2647	.5170	0.67	0.0082
105	180,80,13	28.87	.3532	.5280	29.72	.3316	.5264	2.93	0.0217
122	150,150,160	52.69	.2005	.3994	57.51	.1995	.4213	9.15	0.0220
124	90,35,18	10.32	.2638	.5063	10.54	.2614	.5151	2.08	0.0091
158	100,7,7	10.33	.2973	.5141	10.32	.2856	.5161	-0.14	0.0119
159	7,7,80	9.14	.1790	.3575	9.11	.1834	.3805	-3.17	0.0234
172	255,7,7	49.52	.4305	.5241	49.62	.4014	.5232	0.21	0.0291
200	12,79,90	14.35	.1687	.3916	14.99	.1727	.4119	4.47	0.0207
209	100,55,116	17.48	.2045	.3464	17.98	.2071	.3664	2.84	0.0201
237	30,30,30	7.89	.2007	.4785	7.88	.2040	.4916	-1.14	0.0135
241	16,44,18	8.37	.1981	.5034	8.32	.2003	.5149	-5.62	0.0118

$$\begin{pmatrix} Y_R \\ Y_G \\ Y_B \end{pmatrix} = M_P^{-1} \begin{pmatrix} X_S \\ Y_S \\ Z_S \end{pmatrix} \tag{8}$$

To obtain X_S, Y_S, and Z_S, subtract the dark-field values X_D, Y_D, and Z_D from the XYZ tristimulus values which describe the desired color: $X_S = X - X_D$, $Y_S = Y - Y_D$, $Z_S = Z - Z_D$. The values of Y_R, Y_G, and Y_B obtained from the equation are then compared with the dark-field corrected calibration data in order to find an RGB code for producing the desired color.

It is instructive to apply the matrix method for code selection to both CRT and LVP, then to compare the results. Table 8 shows the application to the Hitachi A CRT. The nine colors in the "Color Requested" column came from the Scene Color Study discussed in Section II. The values in the Y, u', v' column were taken directly from the radiometric measurements on the modelers' Mitsubishi monitor; these values represent a colorimetric description of the color intended by the modeler. However, this Hitachi CRT differed greatly from the modeler's CRT in its luminance range; its blue primary had a maximum luminance only 1/8 as high as the corresponding primary on the Mitsubishi. Therefore, the luminances of the requested colors were reduced to 1/8 of their original value. The effect of this scaling upon the XYZ values to be entered in equation (7) is shown in the column of Table 8 labeled "Scaled X,Y,Z." This change does not affect the u' and v' values, which are independent of absolute luminance level. Neither should it affect the general appearance of the display, since all areas have been decreased in luminance by the same factor.

The middle section of Table 8 shows the computation of RGB codes and their evaluation for accuracy. When the scaled XYZ values were entered in equation (7) and multiplied by the inverse of matrix M_P, the RGB luminances were obtained. These values were then compared with the CRT's calibration table to find the RGB code which was expected to give the RGB luminances. This RGB code was then used to produce a color on the CRT, and the color output was measured with the radiometer. The resulting values are displayed in the column "Measured Y,u',v'," and the errors in luminance (Y) and u',v' distance are shown in the "Error" column.

As this table shows, the measured Y, u' and v' values were reasonably close to the colors requested. In five cases these values met the criteria for accuracy (5% error or less in Y, .0050 or less in u',v' distance), and it was not necessary to change the computed code at all. For the remaining four colors, the RGB code was manipulated by trial and error until a code was found which produced a color within these limits. The third section of the table shows the successful code, its radiometrically measured Y, u' and v', and the error calculation. Both luminance and chromaticity were matched to criterion for all colors.

Table 9 shows the corresponding code selection results for Talaria. It was again necessary to reduce the requested luminances so that they would fit within the range available from the SLVP. The column "Scaled X,Y,Z" represents an 8% reduction of the original requested values.

Table 8. Code Selection for Hitachi A CRT

Scene area	Color requested		Computed code and results				Successful code and results		
	Original Y,u',v'	Scaled X,Y,Z	RGB luminances	RGB code	Measured Y,u',v'	Error in Y and u'v'	RGB code	Measured Y,u',v'	Error in Y and u',v'
	460.5	56.44	108.70	227	57.22	0.5%			
A: Hangar Roof	0.1973	57.56	305.14	231	0.1968	0.0011	Same		
	0.4528	74.75	46.67	255	0.4518				
	371.3	43.29	68.41	187	46.43	0.04%			
B: White Door	0.1852	46.41	267.33	218	0.1855	0.0005	Same		
	0.4586	57.49	35.56	227	0.4582				
	304.7	36.26	63.96	181	37.89	0.5%			
C: Hangar Front	0.1913	38.09	209.26	196	0.1912	0.0017	Same		
	0.4518	50.34	31.48	216	0.4501				
	179.9	21.14	35.61	141	22.43	0.3%			
D: Horizon Sky	0.1884	22.49	125.45	158	0.1889	0.0017	Same		
	0.4510	30.09	18.84	176	0.4494				
	111.4	14.01	42.20	152	14.53	4.3%	150	14.17	1.7%
E: Foreground	0.2386	13.92	67.93	123	0.2398	0.0013	121	0.2402	0.0016
	0.5336	3.99	1.27	65	0.5331		63	0.5332	
	62.7	10.54	7.10	72	7.05	-10.1%	72	7.85	0.2%
F: Zenith Sky	0.1744	7.84	29.46	88	0.1592	0.0233	86	0.1766	0.0026
	0.2918	37.90	26.17	200	0.2741		195	0.2931	
	52.2	5.37	11.87	89	6.67	2.3%			
G: Background	0.1973	6.52	39.76	99	0.1992	0.0019	Same		
	0.5395	1.86	0.56	50	0.5367				
	40.5	4.69	7.38	73	5.35	5.8%	67	5.02	0.6%
H: Taxiway	0.1848	5.06	28.68	87	0.1870	0.0098	85	0.1832	0.0016
	0.4485	6.99	4.33	103	0.4418		97	0.4481	
	6.5	0.76	1.27	35	1.01	25.5%	30	0.81	1.1%
I: Black Door	0.1883	0.81	4.50	44	0.1885	0.0065	40	0.1864	0.0046
	0.4514	1.07	0.67	53	0.4449		46	0.4528	

Table 9. Code Selection for Talaria

Scene area	Color requested		Computed code and results					Successful code and results		
	Original Y,u',v'	Scaled X,Y,Z	XYZ w/o Dk Fld	RGB lumins.	RGB code	Measured Y,u',v'	Error in Y and u'v'	RGB code	Measured Y,u',v'	Error in Y and u',v'
	460.5	361.2	347.7	74.7	202	318.7	-13.5%	227	306.1	-16.9%
A: Hangar Roof	0.1973	368.4	354.4	201.4	178	0.1908	0.0065	170	0.1970	0.0003
	0.4528	478.3	450.0	73.4	255	0.4528		255	0.4528	
	371.3	270.0	256.5	43.3	122	265.5	-10.6%	138	275.1	- 7.4%
B: White Door	0.1852	297.0	283.1	181.2	162	0.1805	0.0051	165	0.1863	0.0012
	0.4586	367.9	339.6	58.6	161	0.4525		161	0.4590	
	304.7	232.1	218.6	42.7	119	214.4	-12.0%	131	230.1	- 5.6%
C: Hangar Front	0.1913	243.8	229.8	136.0	126	0.1863	0.0076	134	0.1903	0.0010
	0.4518	322.2	293.8	51.1	135	0.4461		135	0.4520	
	179.9	135.3	121.8	22.8	72	134.6	- 6.4%	75	145.5	1.1%
D: Horizon Sky	0.1884	143.9	130.0	78.7	80	0.1876	0.0078	88	0.1870	0.0014
	0.4510	192.6	164.2	28.5	62	0.4432		62	0.4507	
	111.4	89.7	76.2	22.8	73	88.5	- 0.6%			
E: Foreground	0.2386	89.1	75.2	53.8	57	0.2374	0.0051	Same		
	0.5336	25.5	- 2.8	- 1.4	0	0.5286				
	62.7	67.5	54.0	14.3	51	46.7	- 6.9%	50	62.9	25.3%
F: Zenith Sky	0.1744	50.2	36.7	-17.2	0	0.1973	0.0557	0	0.1718	0.0264
	0.2918	242.6	214.2	39.2	43	0.3426		90	0.3181	
	52.2	34.4	20.9	3.2	15	45.6	9.3%	45	118.3	183.8%
G: Background	0.1973	41.7	27.8	28.0	31	0.1916	0.0337	88	0.1956	0.0017
	0.5395	11.9	-16.4	- 3.4	0	0.5063		0	0.5391	
	40.5	30.0	16.5	3.0	14	30.3	- 5.4%	11	33.5	3.5%
H: Taxiway	0.1848	32.4	18.4	12.7	13	0.2049	0.0368	15	0.1850	0.0014
	0.4485	44.6	16.3	2.8	0	0.4793		3	0.4499	
	6.5	4.84	- 8.7	0	0	13.7	166.0%	4	22.1	329.1%
I: Black Door	0.1883	5.15	- 8.8	0	0	0.1778	0.0462	6	0.1882	0.0026
	0.4514	6.88	-21.5	0	0	0.4064		0	0.4540	

These XYZ values were then reduced by the dark field XYZ values, X_D, Y_D, and Z_D. The column labeled "XYZ w/o Dk Fld" shows the resulting XYZ values, which were then entered in equation (8) to obtain the RGB luminances needed from the RGB signal to produce the requested colors. These are, of course, the luminances which were needed in addition to the dark field's own contribution to the final output.

The remainder of the table parallels Table 8. RGB codes were found by comparing the RGB luminances with the calibration tables. The codes were used, the outputs were measured and entered under "Measured Y,u',v'," and the resulting errors were entered under "Error in Y,u',v'." Since only one color came close to the criteria for accuracy (color E), RGB codes for the remaining colors were manipulated to get the best match possible from Talaria.

Color F, "Zenith Sky," could not be matched in either luminance or chromaticity; its color lies outside the triangle defining the gamut limits for this LVP. Although it was possible to find a close u',v' match for the other 8 colors, there were 5 for which the luminance criterion could not be met. Colors B and C were a little too bright to reach the 5% criterion, but their luminances were well within 10% of the requested values. The deviations of 3 other colors were more substantial. At the lowest luminance permitting a color match, the luminances of colors G and I were still too high. At the highest luminance permitting a color match, the luminance of color A was still too low. These failures to obtain the desired luminance level indicate once more that the duplication of natural scenes--and even of CRT displays--with simulator LVPs is not possible because of the restricted range of luminances available. The darkest area cannot be made dark enough, relative to the rest of the display, and the lightest area cannot be made light enough.

In summary, these examples show that the matrix method can be used to select RGB codes for LVPs, provided the dark field is taken into account by using equation (8) instead of equation (7). However, the resulting codes will usually be acceptable only for a proportion of the requested colors. Even with the CRT, some minor code adjustments are likely to be necessary, especially if the application requires high accuracy in color rendering. In order to automate such code adjustments, AFHRL has adopted a computer-controlled iterative search procedure which is based on piecewise linear interpolation with variable chromaticity. This method of producing desired colors is described in detail by Post and Calhoun (1989), who have applied it to CRTs in an updated version of the CRT Colorimetry System mentioned above (page 23). The application to LVPs differs only in the introduction of a dark-field correction.

For devices such as LVPs, whose technology differs greatly from CRT technology, additional decisions need to be made in order to secure the optimal rendering of scenes designed on a CRT. Differences in color gamut and range of contrast require adjustment of the scene colors so that the total effect of the scene is transferred as faithfully as possible to the large-screen projected display. Since there are many ways to carry out such a transformation from one device to another, choice of a best method will require new experimental evidence.

V. UNIFORMITY OF LUMINANCE AND CHROMATICITY

Light-valve projectors offer large display areas at acceptable luminance levels. This section provides information on the uniformity of luminance and chromaticity across the display area. It will include measurements made in June 1988, after factory modifications to the MLVP and after the light-valve in the SLVP had just been replaced.

For these measurements, the LVPs were set up side-by-side to project their displays on a uniform-gain rear-projection screen. The spectroradiometer head was placed 5 feet in front of the center of the display. The distance between projector lens and screen (approximately 45 inches) was chosen so that each display subtended 28^{o} horizontal by 21^{o} vertical at the spectroradiometer viewpoint. The display can, therefore, be thought of as containing nine equal sectors, each approximately $9^{o} \times 7^{o}$, in a 3x3 array.

A graphics program was used to place a marker at the center of each of these nine sectors. When the spectroradiometer is aimed at one of these dots, its luminance and chromaticity readings are based on the light coming from a $1.5^{o} \times 0.5^{o}$ area at the center of that sector. Once the meter was positioned and focused, the marker program was replaced by a uniform display at maximum white (255,255,255), red (255,0,0), green (0,255,0), or blue (0,0,255), and each of these displays was scanned three times, so that the data obtained are averages of three measurements. This procedure was repeated at each of the nine markers.

Figure 20 shows relative luminance data for the Talaria SLVP. As expected, the luminance of all primaries and of white was greatest in the center sector. Therefore, the luminance of that sector was taken as the reference value, and luminance of all other sectors is shown in the figure as a percentage of the center luminance. The results for red, green, blue and white are shown separately.

As Figure 20 shows, all primaries suffered attenuation at positions away from the center, and green showed more attenuation than red or blue. The corners of the display tended to have lower luminance than the middle sectors on each side, but the amount of attenuation varied greatly from corner to corner. For this display, the lower right corner was quite dim relative to the center.

The corresponding data for the MLVP appear in Figure 21. Red was attenuated more than green or blue at most positions. As with the SLVP, the corners suffered more attenuation than the middle sectors. The pattern of attenuation was different from the pattern obtained for the SLVP, but the amount of variation was similar.

These variations in luminance are accompanied by noticeable changes in chromaticity. Figure 22 shows the u',v'-coordinates for all 36 measurements on each display. The green primary showed least variability in both SLVP and MLVP displays. The chromaticity of white varied significantly from one sector to another, and this variability was greater for the MLVP than for the SLVP. Figure 22 also shows this SLVP as having

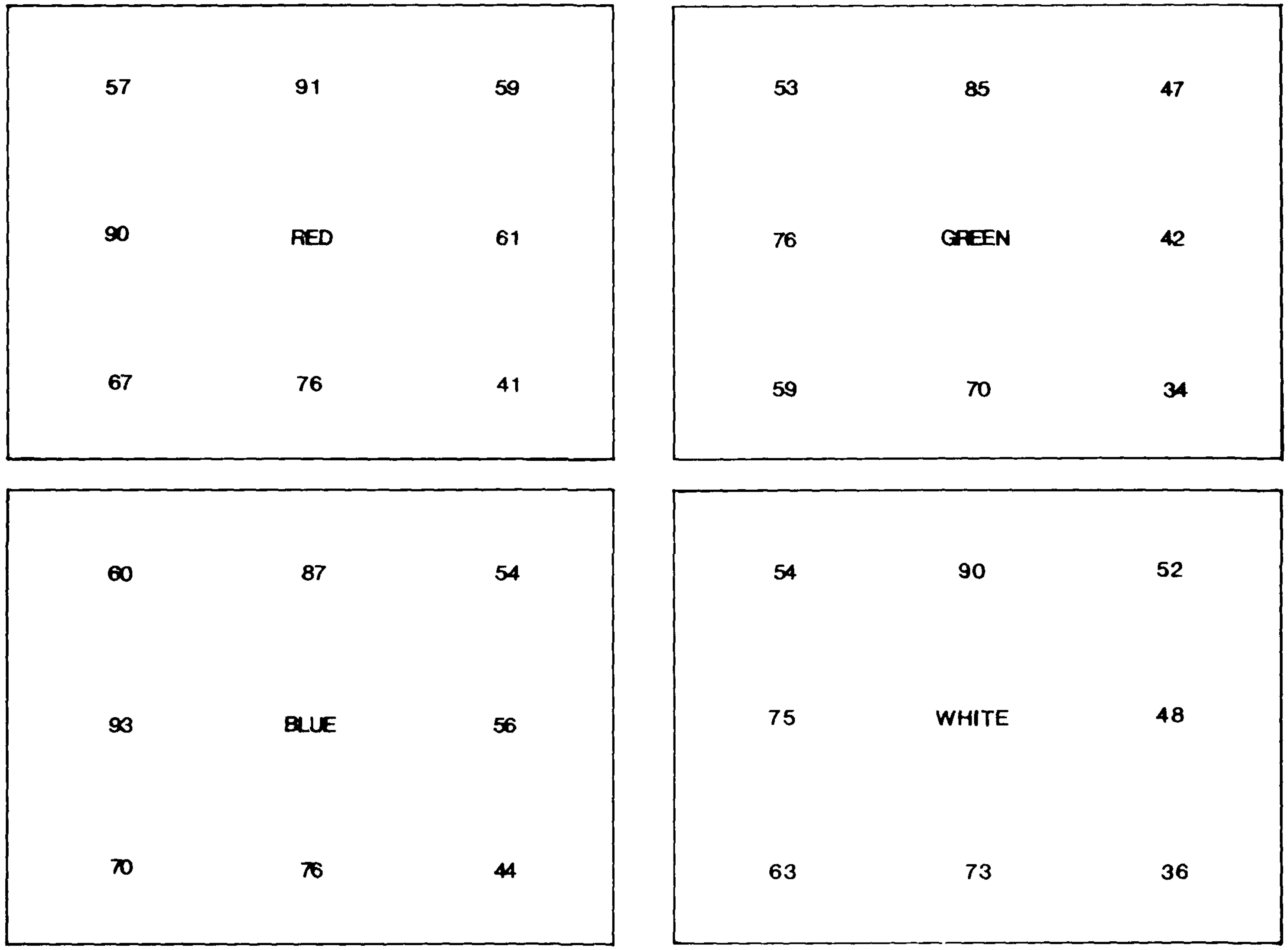


Figure 20. Variability of Luminance in SLVP Display. Each section shown above represents luminance variations within a full-screen solid color display at maximum video level. Taking the luminance at the center as 100%, numbers in the sections indicate luminance measured at the other 8 positions as percent of center luminance.

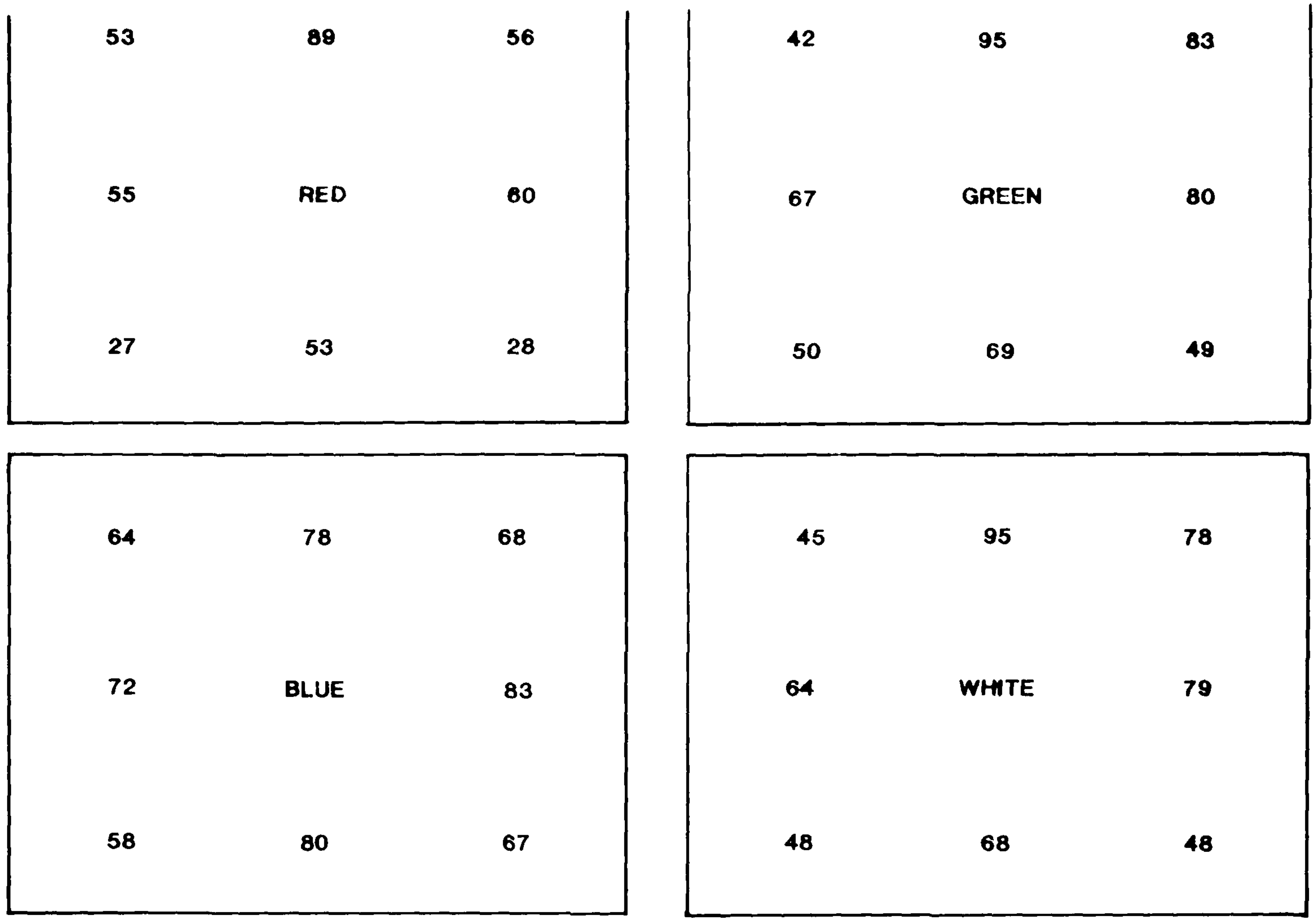
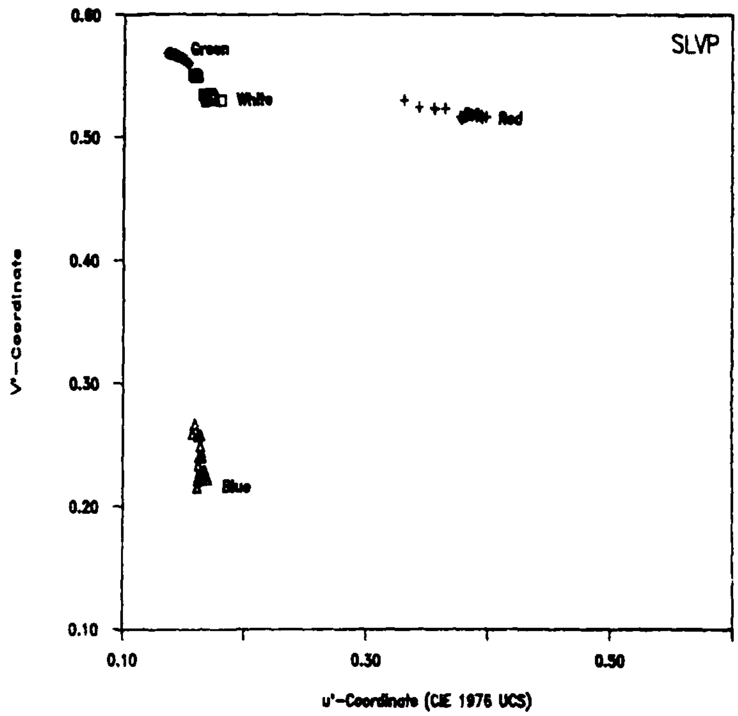


Figure 21. Variability of Luminance in MLVP Display. Each section shown above represents luminance variations within a full-screen solid color display at maximum video level. Taking the luminance at the center as 100%, numbers in the sections indicate luminance measured at the other 8 positions as percent of center luminance.



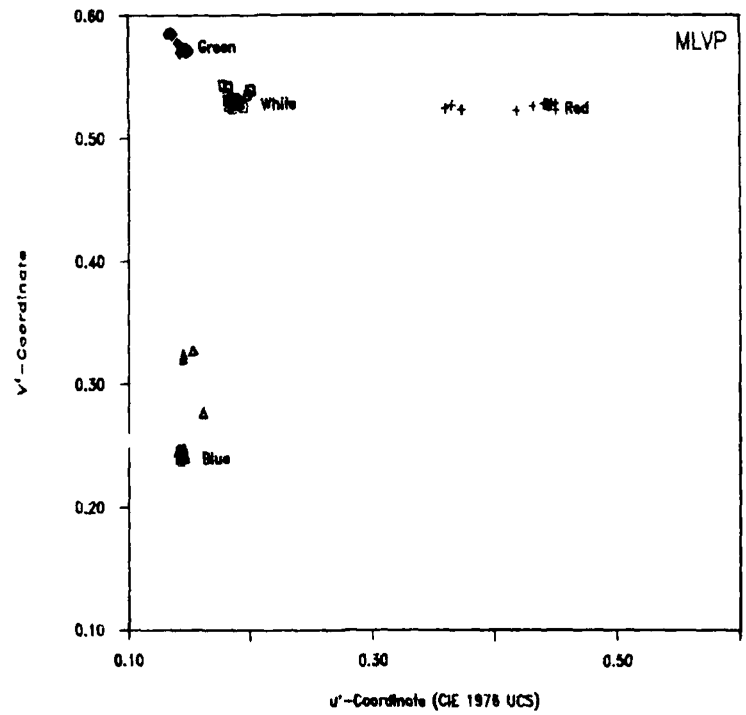


Figure 22. Variations in Chromaticity Among Display Sectors. Measurements of chromaticity at maximum output for three primaries and white at the center of each of nine equal sectors of the display. Top: Talaria SLVP; bottom: MLVP. Measurements made in June 1988.

a smaller color gamut than that of the unit measured earlier for Figure 16. Comparison with Figure 16 will show that the previous Talaria's gamut was approximately the same as that of the MLVP in Figure 22.

VI. STABILITY OF LUMINANCE AND CHROMATICITY OVER TIME

The luminance output of a xenon arc tube decreases over time; therefore, it is to be expected that the luminance of an LVP will gradually change as its source changes. During the period from 22 October 1987 to 1 December 1987, members of the General Electric (GE) staff at AFHRL performed daily measurements to track luminance and chromaticity variations of both the SLVP and the MLVP. These measurements, supervised by Susan Baroff, were undertaken as part of an effort to achieve a better understanding of the factors affecting LVP luminance and chromaticity so that improvements could be made in routine maintenance and adjustment procedures.

The IRIS 3030 computer graphics system served as the image generator for the displays. Before this measurement series began, both the Talaria and the MLVP were aligned to produce unimodal SEDs for red, green, and blue output at video level 64. This level was chosen for alignment because earlier GE research had shown that adjustment at low video levels ensures high color purity at all levels.

Luminance output of LVPs fluctuates for approximately 2 hours after the projector is put into operation (OPERATE and VIDEO on); therefore, the daily measurements were preceded by a warmup period of at least 2 hours. Then, starting at about 1600 hours, a rear-projection screen was set up 4 feet from the projectors, and the projectors were focused. The IRIS system produced a four-color display on the screen, with red in the upper left quadrant, green in the upper right, blue in the lower right, and white in the lower left. All colors were set at video level 32. The Photo Research radiometer was positioned 7 inches from the center of one of these quadrants, one radiometric scan was performed, and data were recorded including luminance and x,y chromaticity coordinates. This procedure was repeated for the other three quadrants. Then the video level of the display was increased to 64, and all measurements were repeated. Measurements were made in similar fashion at three more video levels (121, 181, and 255).

Before the day's measurements were concluded, records were made of voltages at the IRIS and at specific test points on each projector. IRIS output voltages at maximum red, green, blue and white were found to remain constant throughout the measurement period. Voltage readings at the operator control unit (OCU) verified that no manual color or brightness adjustments were made during the 5-week period of measurements. Other voltage measurements indicated the extent to which line voltage fluctuations were being compensated. Input line voltage was also measured and recorded.

During this period, the RMS line voltage was found to fluctuate between 201 and 207 volts. Line voltage fluctuations of this magnitude

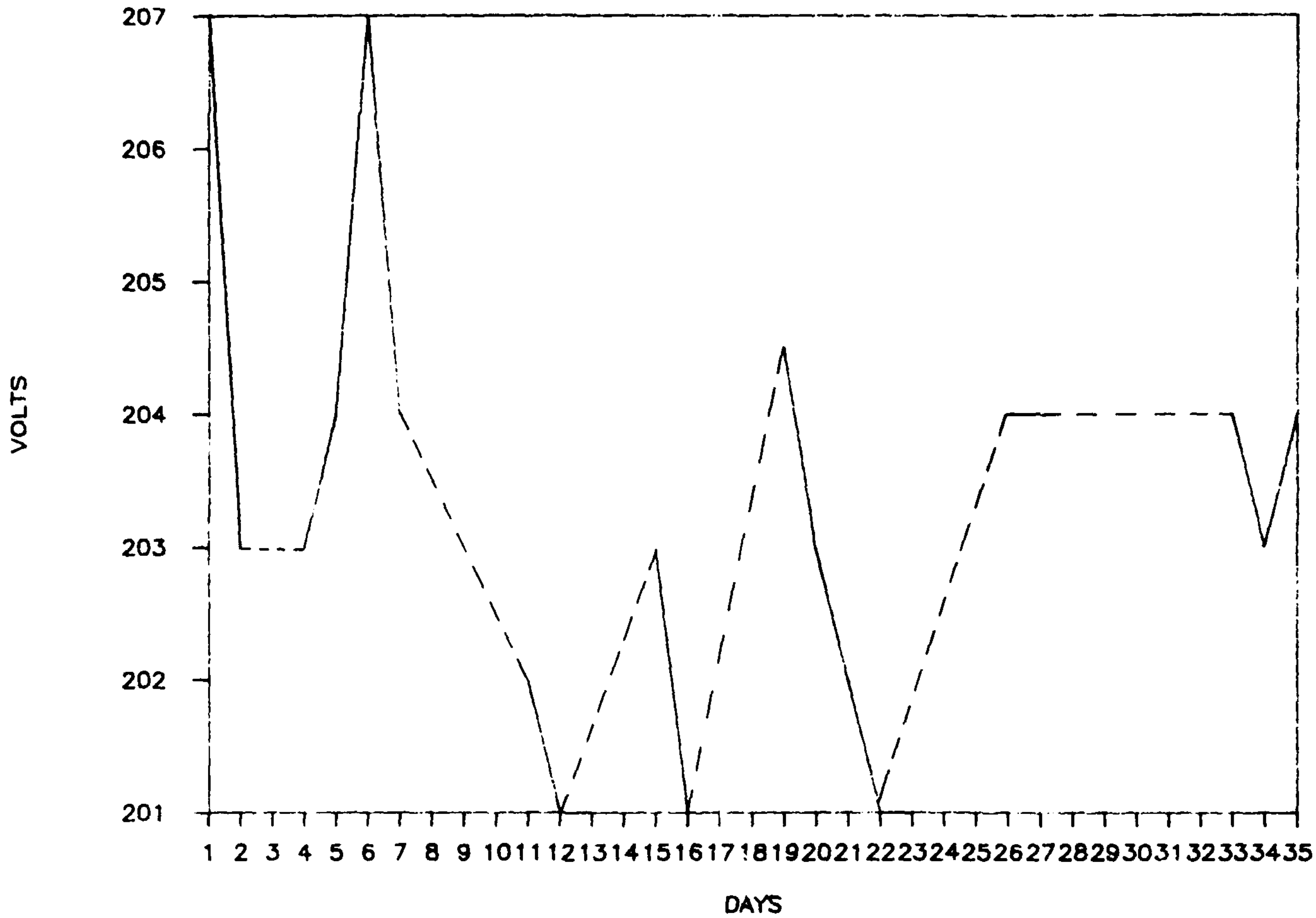


Figure 23. Day-to-Day Variations in Input Line Voltage. Measurements were made over a 35-day period in November and December 1987. Points connected by solid lines indicate measurements made on successive days. Dotted lines indicate days when measurements were not taken.

did not usually affect voltage measures internal to the Talaria and the MLVP, as each projector is provided with circuits designed to maintain constant internal voltages when line voltage varies within a range from 190 to 260 volts. However, during the data collection period, there were two occasions on which the line voltage shifted 3 volts or more from one day to the next. Figure 23 shows these variations in line voltage; dotted lines represent weekends, during which no measurements were made. Note particularly the large deviations at day 6 (2 November) and day 19 (15 November). In spite of internal compensating circuitry, voltages at the lamp and a few other checkpoints inside the SLVP shifted in response to both of these large deviations in line voltage. Internal voltages of the MLVP shifted during the second deviation but not during the first.

Figure 24 displays the variations in luminance output over this time period. All curves are for video level 255 (maximum output). The upper graph shows the output of Talaria's primaries individually and in combination (all primaries at 255, producing white); the lower graph shows MLVP output. The green primary shows the greatest variability in both

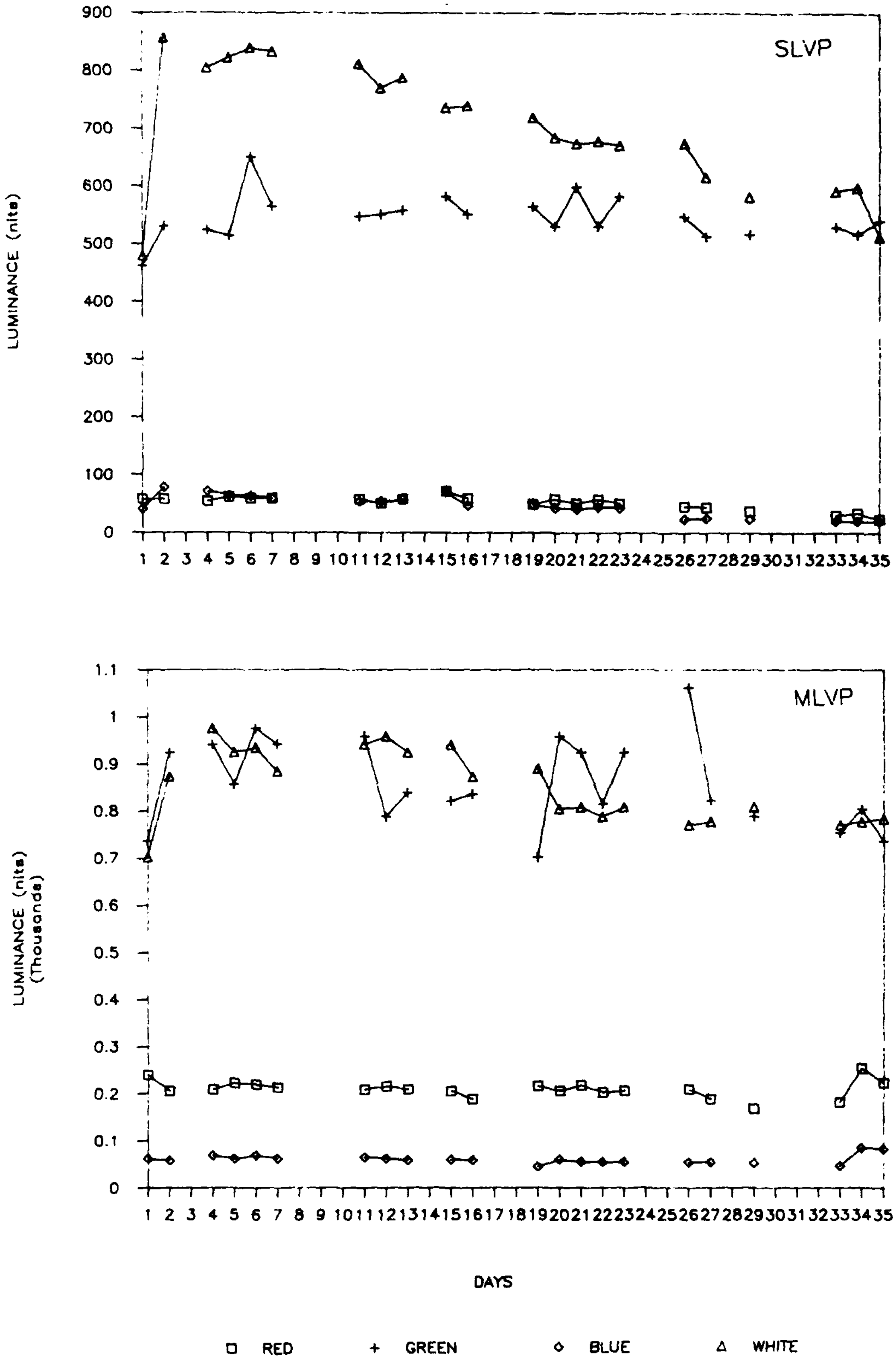


Figure 24. Day-to-Day Variations in LVP Output Luminance. Measurements were made over a 35-day period at maximum output of three primaries and white. Top: Talaria SLVP; bottom: MLVP.

projectors, and there are variations which coincide with the large voltage deviations on days 6 and 19. The main systematic change in luminance for both projectors was a gradual decline as the arc tube sources underwent aging. The MLVP began the period at 551.6 hours on its run-time meter, and ran to 793.1; the SLVP began at 871.5 and ran to 1135.1. The SLVP's light valve was replaced shortly after this measurement period.

Figure 25 shows the variations in chromaticity of both LVPs during the measurement period. The x,y chromaticity coordinates have been converted to u',v' values and plotted in uniform chromaticity space. A comparison of Figure 25 with Figure 22, drawn to the same scale, shows that the chromaticity changes over time were somewhat larger than the chromaticity variations from one sector of the display to another.

These changes in chromaticity appear to be related more to arc tube aging than to line voltage changes. Some of the deviations in chromaticity occurred toward the end of the measurement period. This was true of the shift in SLVP white toward green, attributable to a gradual leftward drift of its green primary. Another deviation which occurred late in the series is shown in the MLVP graph by the three white points which shifted to the upper right; this change can be attributed to a gradual leftward shift of the MLVP's red primary throughout the period and an upward shift of its blue primary during the final week of measurements. In only one instance did the changes appear to be related to the line voltage fluctuations: The four points above and to the left of the main white group for the MLVP represent measurements made at the time of these shifts. There were no changes in any of the primaries which corresponded to the line voltage changes.

These longitudinal measurements provide evidence of the rate at which LVP luminance declines over time. They also show that chromaticity may vary systematically as luminance declines, but the pattern of change may differ from one projector to another. Although compensating circuits are not able to maintain steady internal voltages during large line voltage fluctuations, it is not clear that either luminance or chromaticity is affected by such fluctuations. Additional data will be obtained when direct control over line voltage changes becomes possible.

VII. CONTRAST AND RESOLUTION

Section II of this report included information on the contrast ratios found in simulator displays under several conditions. A ratio as high as 27:1 could be confirmed only for the condition under which a large area at maximum luminance (RGB code 255,255,255) was compared with a large area at minimum luminance (the dark field, RGB code 0,0,0). When these same luminances were compared in smaller areas adjacent to each other (the white hangar and its black door), the contrast ratio was only 18:1. When dark green objects were shown on a yellowish tan ground in the object density experiment, it was impossible to obtain contrast ratios better than 5:1. If anything meaningful is to be said about the contrast available in SLVP and MLVP displays, contrast measurements must be made for many areas which differ in size and in color.

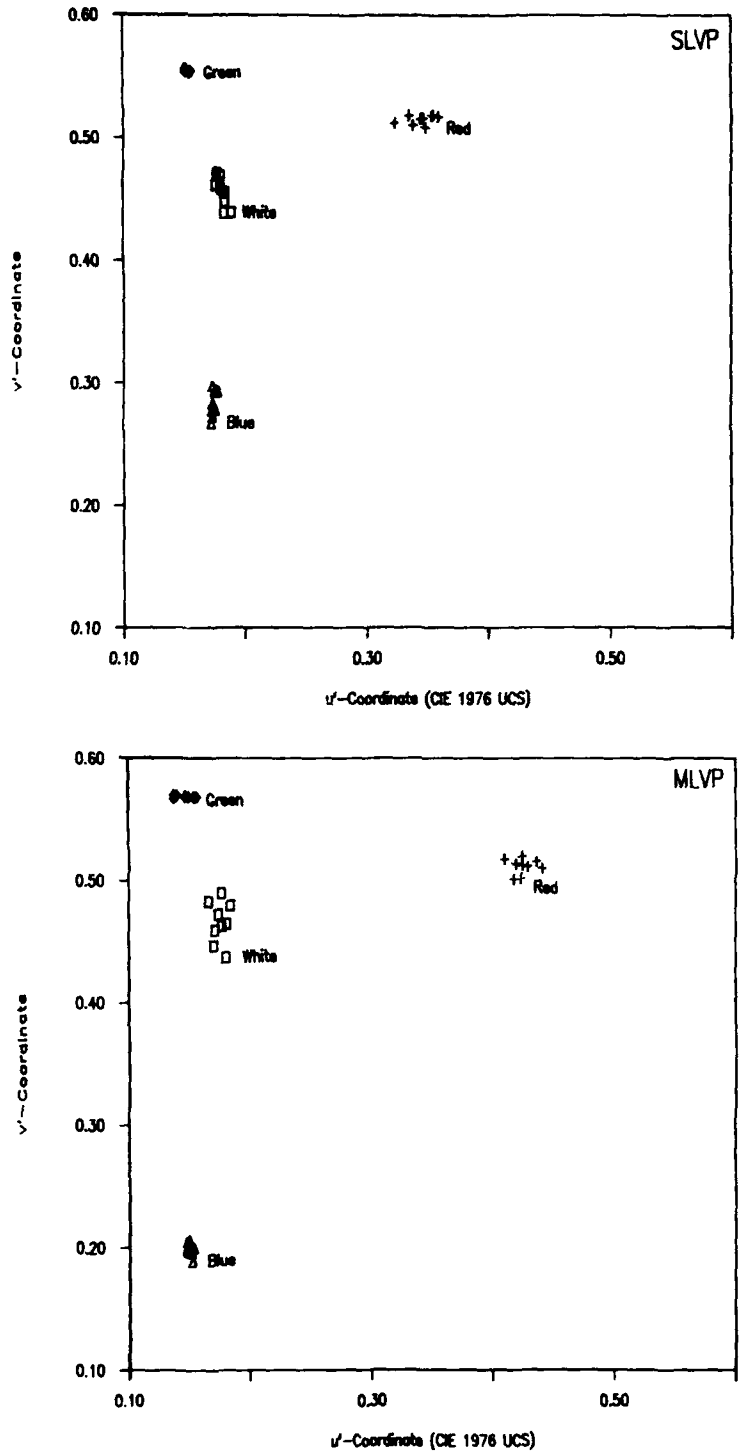


Figure 25. Day-to-Day Variations in LVP Chromaticity. Top: Talaria SLVP; bottom: MLVP. This figure may be compared with Figure 22, but it should be remembered that the data in Figure 22 derive from June 1988, after the MLVP had been upgraded and the SLVP had been supplied with a new light valve. Measurements for this figure were made in November and December 1987.

In other words, the luminance contrast of a display cannot be discussed apart from the resolution of the display. Displays with high resolution permit viewers to detect the luminance difference (contrast) between an object and its background when the region representing the object is relatively small. For any given display, as the size of a region decreases, its contrast with the background will decrease, until a limiting size is reached beyond which the contrast is no longer sufficient to permit the viewer to detect its presence. To characterize display resolution, then, it is necessary to know how much contrast is available for regions of small size. To evaluate a display's usefulness for a certain purpose, it is also necessary to know how much contrast is required by an average viewer in detecting regions of various sizes.

Crane, Gerlicher, and Bell (1985) obtained SLVP resolution thresholds for stationary and moving targets (Landolt Cs) at 60, 80, and 100 ftL. They found that the line width and gap size at threshold were 2 to 3 arc minutes for stationary targets and varied between 1.8 and 2.5 arc minutes, depending on direction and speed of movement, for moving targets. Contrast was set to a light/dark ratio of 13:1 for a target of a standard size positioned at the center of the display. Actual display contrasts therefore varied as the target decreased in size and moved across the display area. The study did not include measurements of these contrast changes.

For this report, actual display contrast has been studied in relation to both size and color. The measurements to be reported in this section follow as closely as possible the current methods used in measuring and describing monochrome CRT displays. There are some difficulties inherent in applying these methods to full-color displays of any kind, and there are special difficulties in applying them to color light-valve displays. However, data obtained by these methods do enable the user to compare single and multiple LVPs with each other, and with CRTs, on the basis of some common principles of measurement.

Line Width Measurements

Resolution can be approached by measuring the width of the narrowest line which can be drawn on a display. Figure 26 shows the luminance profile of a single-pixel horizontal white line on an MLVP display. This profile was recorded by the Photo Research PR719 Spatial Scanner directed at the center of the display.

Using such a profile, line width may be defined in various ways. It will be defined here as the width of the line at 50% of the line's maximum luminance, following the practice recommended by Murch and Virgin (1985). On a CRT screen, line width can be described in millimeters and related to the screen size. For a large-screen projection display, the choice of units for describing line width requires some deliberation.

A decision must first be made about display size. Projection lenses are typically optimized for a certain range of display sizes; optimal resolution measurements should therefore be made on displays within that range. Since the projection lenses in the LVPs were optimized for an 8- to 20-foot diagonal display, the line shown in Figure 26 was recorded from

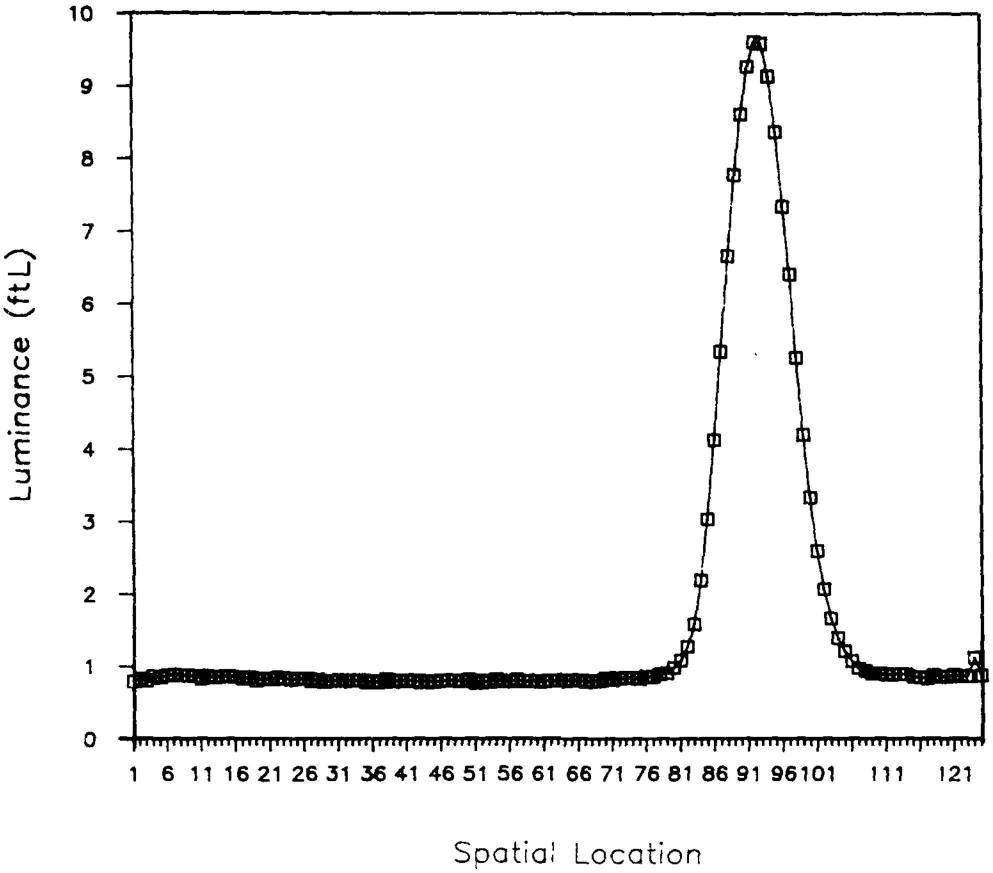


Figure 26. Luminance Profile of a Single-Pixel Line. Measurement made on a maximum luminance white horizontal line, 1 pixel wide, projected at the center of the screen by the MLVP.

a display 6 feet high with the screen about 12 feet from the projector. Use of this large-screen display also minimizes any effects of light scatter within the rear-projection screen itself.

Line width on this display can be described in millimeters or inches, as on the CRT, but these units do not provide a meaningful comparison because the displays are of such different size. Line width will therefore be described in units of visual angle, the angle subtended at the eye of an observer who is seated at a standard distance from the display. "Standard" distance is usually taken as a multiple of display height, but the standard varies with display types; it may be 1.5 to 2 screen heights for a typical CRT workstation, 3.3 times screen height for high definition television (HDTV), or 6 times screen height for current NTSC television.

The "standard" distance assumed here is 3 times display height (18 feet for this 6-foot display). This standard approximates the 12-foot viewing distance in the AFHRL dome, judged with respect to the height of the smaller AOI inset ($26^{\circ} \times 20^{\circ}$). By examining the resolution characteristics of LVPs at 3 times display height, this report will provide data which can be directly related to the best resolution conditions in the dome display.

Table 10. Line Widths in LVP Displays*

Color	Single LVP		Multiple LVP	
	Vertical	Horizontal	Vertical	Horizontal
White	2.8	1.8	3.1	3.2
Green	2.8	1.2	3.2	3.4
Magenta	3.3	2.5	2.4	2.9
Red	3.3	2.2	3.1	2.8
Blue	3.3	2.2	2.0	3.1

*All measurements expressed in arc minutes.

Table 10 presents line widths for single-pixel bright lines placed at the center of the display with the dark field as background. Conditions of measurement were identical for both projectors: Display size was the same, and the display controller was an IRIS 4D graphics system. The IRIS 4D is able to select and address 1023 active lines and 1280 pixels per line. When it is used to control the LVPs, the result is a square display, approximately 72 x 72 inches; the usual 4:3 aspect ratio is not possible without loss of color control. Therefore, it should be remembered that Table 10 reports measurements on displays with more nominal pixels per inch in the horizontal direction than in the vertical direction. It might be expected that the measured horizontal width of vertical 1-pixel lines would be less than the measured vertical width of horizontal 1-pixel lines.

In Table 10, the SLVP has consistently wider vertical lines than horizontal lines, regardless of color. The MLVP, on the other hand, does not show much width difference between vertical and horizontal lines. The largest difference is for blue lines, which are substantially narrower when they are vertical. On the basis of these line widths, it may be expected that there will be a difference between horizontal and vertical resolution for the SLVP but not for the MLVP.

Luminance Profiles of Square-Wave Gratings

Grating patterns have been increasingly used during the past 20 years in the study of optical systems. Sinusoidal gratings can be described as having a certain spatial frequency, measured in cycles per unit distance, and the ability of observers to resolve such gratings can be measured in terms of the threshold contrast required to detect the presence of a grating. Contrast sensitivity functions for human observers have been measured at a range of luminance levels (van Nes & Bouman, 1967; van Meeteren & Vos, 1972). Each such function describes the way in which threshold contrast varies with spatial frequency for some mean luminance value.

Monochrome CRT displays are often characterized by functions relating grating contrast to spatial frequency. The next section will present comparable data to characterize LVP displays in these same terms. However, because of the different technology employed in light valves, such repetitive patterns present special problems. The nature of these

problems is revealed in LVP luminance profiles of patterns designed to be square-wave gratings.

Figure 27 presents such profiles separately for the green, magenta, red and blue components of the SLVP. In each of the 4 sections of this figure, horizontal and vertical grating profiles have been superimposed for comparison; horizontal grating profiles are indicated by diamonds, and vertical grating profiles are indicated by crosses. All records shown in this figure were obtained with square-wave patterns in which dark and light bars were of equal width.

The profiles in Figure 27 should be examined in relation to SLVP color control technology, discussed above on page 17. It is relevant here that the green and magenta components, separated by the dichroic filter, are gated through horizontal and vertical slits, respectively. The two upper sections of Figure 27 show the luminance profiles for green and magenta gratings. The profile for vertical green bars is smooth and quite similar to the sort of luminance profiles obtained from CRTs; the profile for horizontal green bars shows periodic fluctuations which seem to reflect the number of pixels per bar (10). These periodic fluctuations are also present in the profile for vertical magenta bars, while the horizontal bars have a rather smooth profile with increased luminance at the edges.

In the two lower figures, the red and blue components of the magenta light are examined separately. For both red and blue, it is the vertical component which shows the pixel-related fluctuations--approximately 10 for the 10-pixel blue bars, 15 for the 15-pixel red bars. Both red and blue horizontal bars show the enhanced luminance at the edges which was seen also in the profile for horizontal magenta bars.

These pixel-sized fluctuations are of interest only because they remind us that light-valve technology has the potential for introducing periodic artifacts or "beats" when the size of scene elements is close to the size of the color-control slots. The fluctuations themselves will not be visible to an observer sitting 3 display heights from the screen; their spatial frequency is above 30 cycles per degree, a frequency range which requires very high contrast if it is to be perceived by the human eye.

Figure 28 shows a similar set of luminance profiles for the MLVP. The profiles for the two main components, green and magenta, show three or four luminance peaks for each 10-pixel light bar. The fluctuations are more noticeable for the vertical green bars than for the horizontal; green is controlled exclusively by one light-valve component in the MLVP, and it is gated through vertical slits. Magenta light is handled by the other light-valve component, with red gated horizontally and blue vertically; the main periodic fluctuations for red are on the horizontal bars, for blue on the vertical bars. In general, however, the profiles are more regular for MLVP colors than for SLVP.

Are there any pronounced phenomenal differences in the appearance of colored gratings on the SLVP and MLVP? A series of 16 gratings was examined in each primary color on each display, with the pixels per cycle varying from 2 to 32. With a set of 16 such gratings visible at once, all

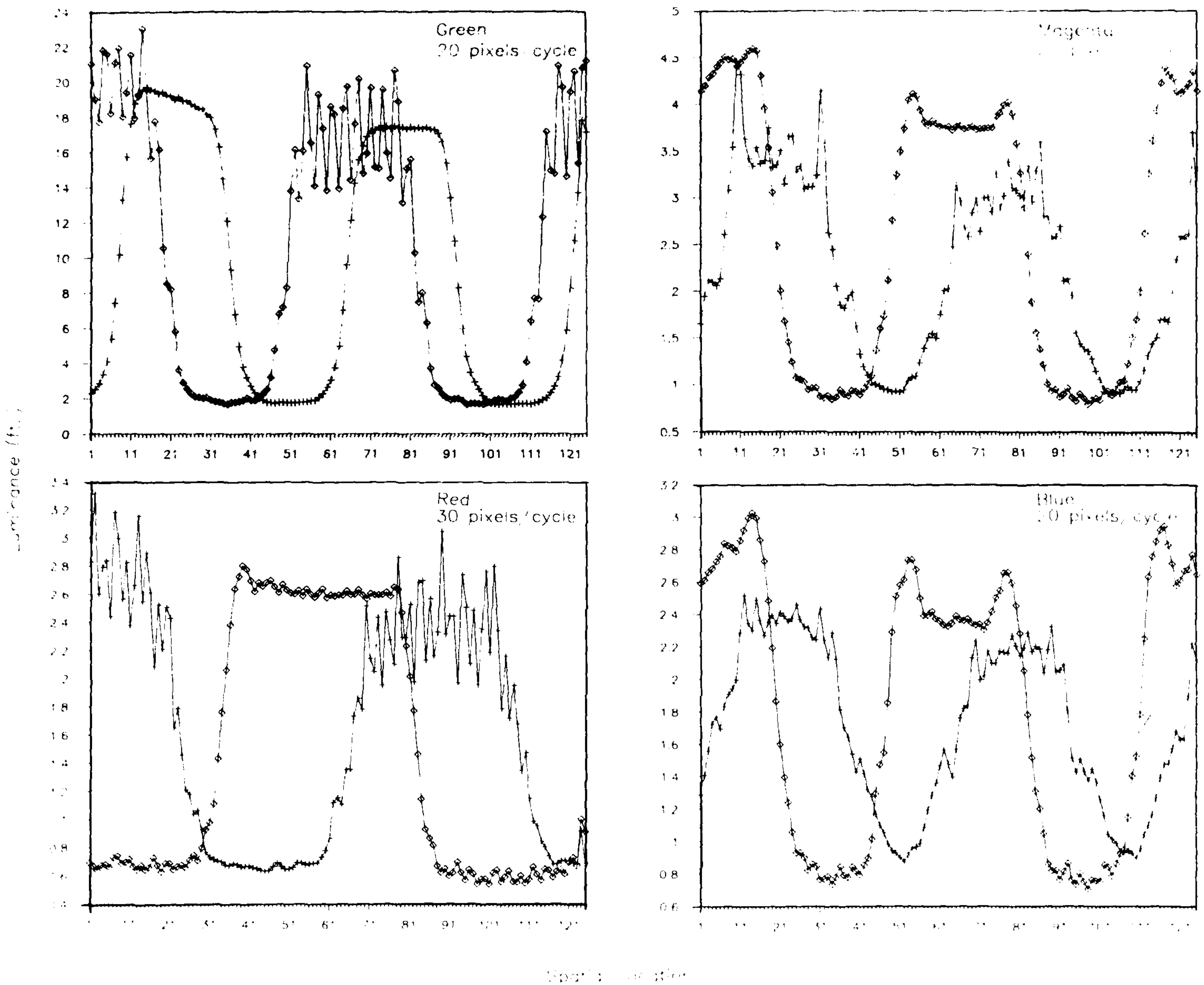


Figure 27. Luminance Profiles of Square-Wave Gratings Displayed by the SLVP. Luminance distribution at central 1.5° of 72-inch square display with IRIS 4D as display controller, programmed to display horizontal or vertical bar patterns. Scans of vertical bars are indicated by crosses, scans of horizontal bars by triangles. Measurements made in January 1989.

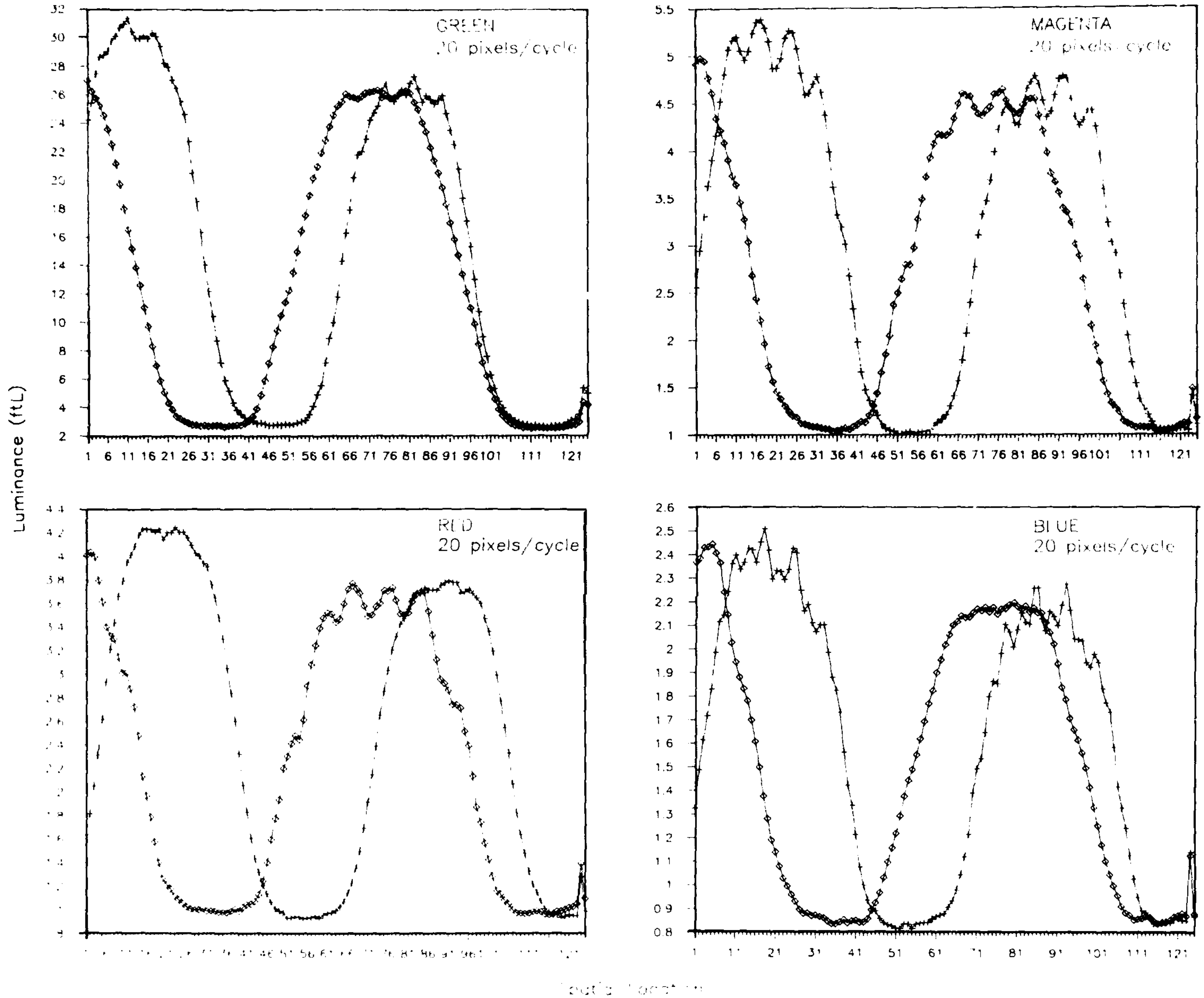


Figure 28. Luminance Profiles of Square-Wave Gratings Displayed by the MLVP. Luminance distribution at central 1.5° of 72-inch square display with IRIS 4D as display controller, programmed to display horizontal or vertical bar patterns. Scans of vertical bars are indicated by crosses, scans of horizontal bars by triangles. Measurements made in January 1989.

nominally in the same color, striking variations in apparent color were observed in the SLVP display, and these variations were greatest for the direction parallel to the gating slits. Thus, for the SLVP the green vertical gratings appeared desaturated for bar sizes from 6 to 14 pixels per cycle. The desaturation arose because, for these relatively high frequency gratings, the dark field between green bars was distinctly reddish. Close inspection showed that the borders of all green bars had magenta fringes on both sides; these borders merged when the bars were narrow and close together. Horizontal green gratings were free of these borders and showed little color variation with spatial frequency.

Red and blue horizontal gratings, on the other hand, tended to have green borders which lay inside the dark bars and which filled them when the bars were sufficiently narrow. Consequently, the red gratings with 4 to 12 pixels per cycle appeared desaturated through mixing with this background of low luminance green; the blue gratings from 4 to 18 pixels per cycle also appeared lighter and greener than the wider gratings.

However, the most pronounced color distortions occurred with red and blue vertical gratings. All the blue vertical bars had pronounced red borders, and with bars of 4 to 20 pixels per cycle these borders tended to give the blue bars some amount of purplish cast. Indeed, the gratings in this range could not be said to be truly blue; instead they were varying shades of magenta. Similarly, the red vertical gratings from 4 to 12 pixels per cycle had a bluish cast. Such color distortions are doubtless traceable to the use of diffraction as a method of color control, and they can be expected to occur in SLVP displays wherever small details are designed to be brightly colored.

The same patterns have much greater color stability in the MLVP display. In our experience, the MLVP requires daily adjustment to maintain its color convergence. Without perfect convergence, white gratings will have magenta fringes on one edge, green fringes on the other. With good convergence, however, the set of 16 green gratings appeared green at all sizes and in both horizontal and vertical orientations; there was no distortion of the dark bars toward magenta or red. Blue vertical gratings all looked blue rather than purplish, but there was some purple in blue horizontal gratings of 4 to 10 pixels per cycle. Red horizontal gratings showed very little color variation, but red vertical gratings appeared desaturated at 4 to 10 pixels per cycle.

In short, these observations indicate that color control in the MLVP is better than in the SLVP. Providing separate projectors for green and magenta removes the major artifacts in green control. Controlling red and blue on separate horizontal and vertical axes reduces the tendency for blue and red to interfere with each other.

Contrast Functions

When sinusoidal gratings are being studied, it is no longer sufficient to describe contrast in terms of a light/dark ratio. Sinusoidal functions vary symmetrically around a mean luminance, and their minimum luminance may be well above anything that could be called "dark." It has become

standard practice to define the contrast of such patterns in terms of the following ratio, often referred to as "Michelson contrast" (C_m):

$$C_m = \frac{L_2 - L_1}{L_2 + L_1} \tag{9}$$

where L_2 is maximum luminance and L_1 is minimum luminance.

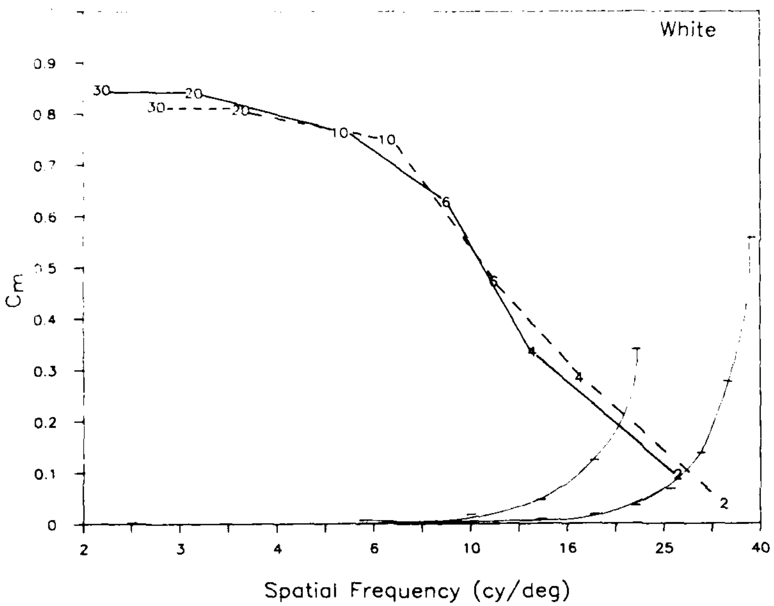
Recordings like those in Figures 27 and 28 were made with the PR719 Spatial Scanner for vertical and horizontal square-wave gratings of 30, 20, 10, 6, 4, and 2 pixels per cycle for white, green, magenta, red and blue color output of SLVP and MLVP displays. For each projector, three of the resulting contrast modulation functions (white, green, and magenta) will be presented. Figure 29 shows these functions for the SLVP; Figure 30 shows them for the MLVP. As explained above, all of these functions are related to spatial frequency in cycles per degree at a viewing distance of 3 times the display height.

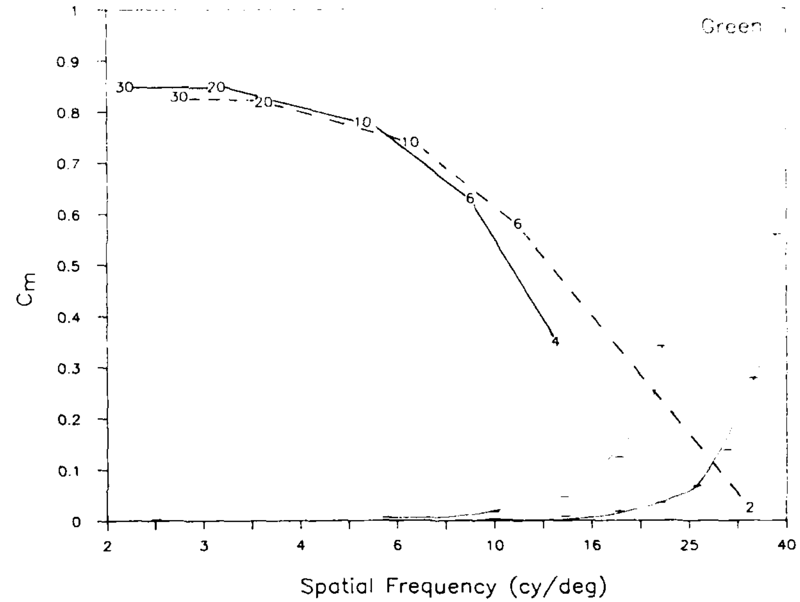
Each of these graphs also shows the approximate location of the contrast modulation threshold for human vision at two luminance levels, 1 nit (left curve) and 15 nits (right curve). The lower luminance level is in the range of the AFHRL dome display. Any point on the contrast modulation function lying to the right of its threshold function represents a combination of frequency and contrast which will not be visible in the dome display. For the SLVP, only the highest measured spatial frequencies (at 2 pixels per cycle, between 25 and 40 cycles per degree) fall beyond the dome threshold curve. For the MLVP, the 3-pixel per cycle gratings (between 12 and 18 cycles per degree) would also be only marginally visible.

No large differences between vertical and horizontal contrast functions are seen in these graphs, except for the SLVP's magenta gratings, where the horizontal function lies above the vertical. SLVP contrast on the vertical appears to be slightly depressed for magenta, which is controlled through vertical gating slits.

When the contrast functions for white, green and magenta are compared in either display, it is clear that the highest contrast levels are obtained when the gratings are green-on-black. Magenta-on-black gratings are the poorest, and white-on-black gratings--made by mixing green and magenta to obtain white--lose some contrast in comparison with the green gratings because of the less efficient magenta performance. It should be remembered that all these functions were obtained with maximum white, green, or magenta output. Proportional attenuation would be obtained if gratings of these pixel widths were composed of less than maximum color output. Therefore, the functions displayed here represent the upper limit of LVP contrast.

Although these data do not fully describe LVP resolution and contrast, they may provide some awareness of the issues involved. Work toward better methods and more adequate description is continuing at AFHRL.





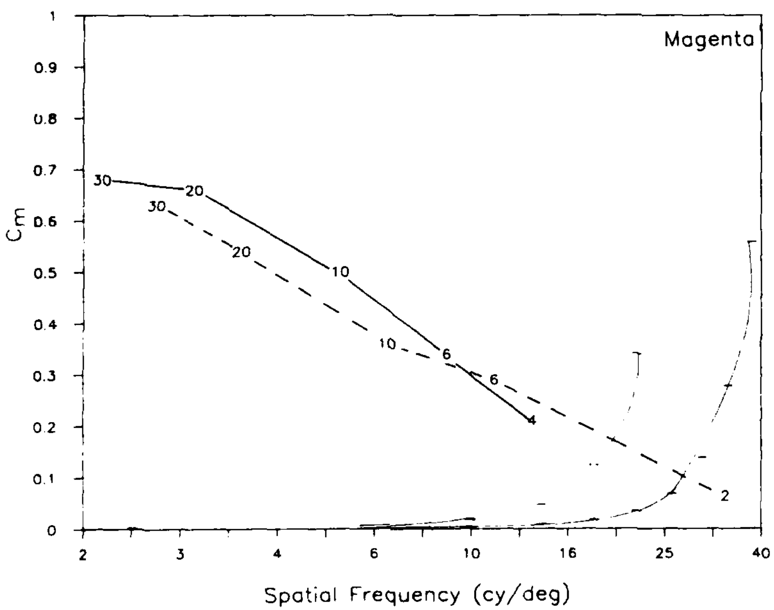


Figure 29. Contrast Functions for the Talaria SLVP. Michelson contrast (C_m) for square-wave gratings of 30, 20, 10, 6, 4, and 2 pixels per cycle (15, 20, 5, 3, 2, and 1 pixel per bar), plotted as a function of spatial frequency at a viewing distance of 3 times the display height of 72 inches. Contrasts for horizontal gratings are connected by solid lines, contrasts for vertical gratings by dashed lines. Curves at lower right represent contrast sensitivity functions for human vision at 1 (left) and 15 (right) nits.

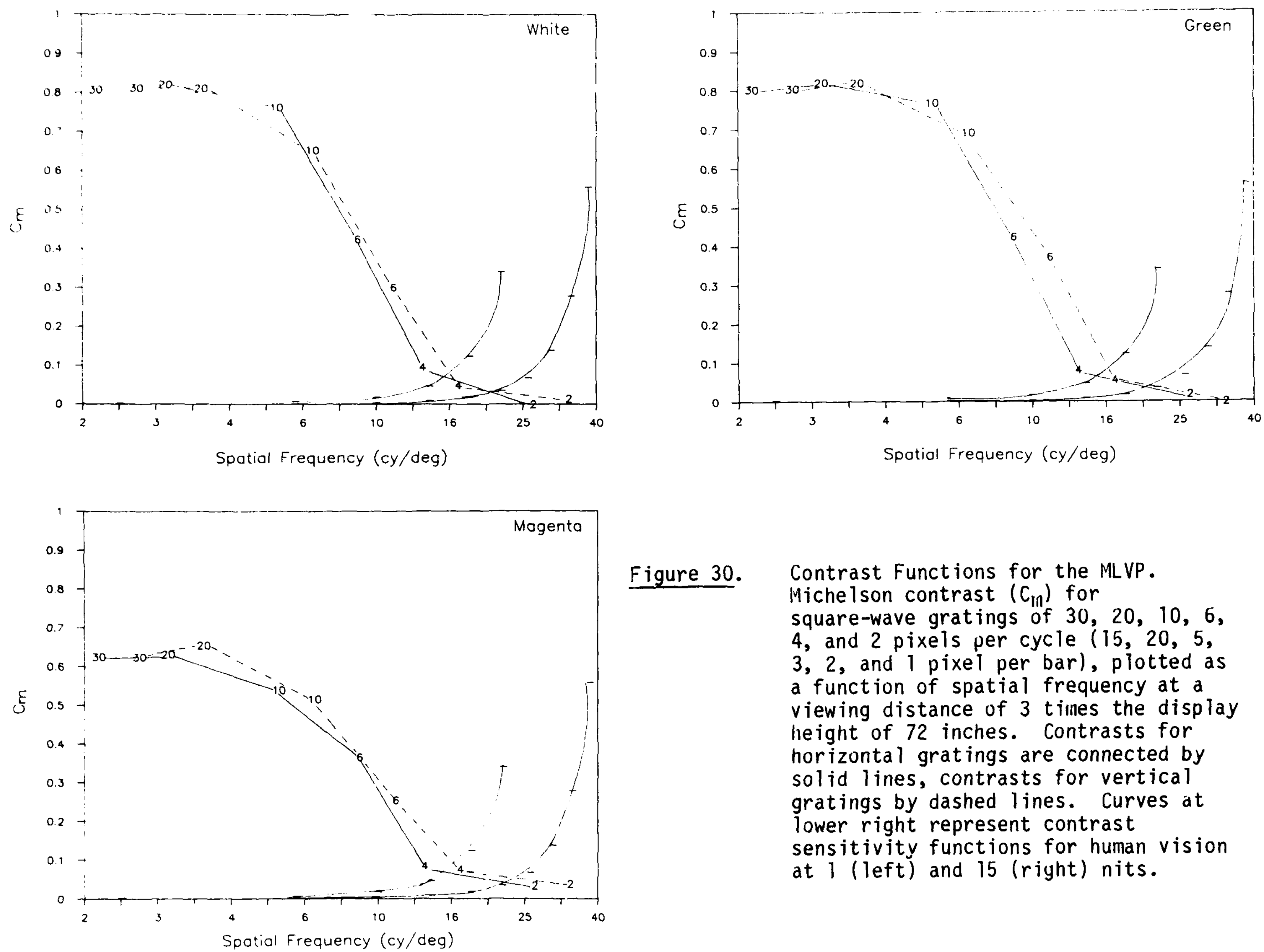


Figure 30. Contrast Functions for the MLVP. Michelson contrast (C_m) for square-wave gratings of 30, 20, 10, 6, 4, and 2 pixels per cycle (15, 20, 5, 3, 2, and 1 pixel per bar), plotted as a function of spatial frequency at a viewing distance of 3 times the display height of 72 inches. Contrasts for horizontal gratings are connected by solid lines, contrasts for vertical gratings by dashed lines. Curves at lower right represent contrast sensitivity functions for human vision at 1 (left) and 15 (right) nits.

REFERENCES

Bartleson, C.J. (1979). Changes in color appearance with variations in chromatic adaptation. Color Research and Application, 4, 119-138.

Crane, P.M., Gerlicher, J.P., & Bell, H.H. (1986). Flight simulator: Comparison of resolution thresholds for two light valve video projectors (AFHRL-TP-85-43, AD-A164 577). Williams AFB, AZ: Operations Training Division, Air Force Human Resources Laboratory.

Judd, D.B., & Wyszecki, G. (1975). Color in business, science and industry (3rd ed.). New York: Wiley.

Howard, C.M. (1989). Color performance of light-valve projectors. Proceedings of the International Society for Optical Engineering (SPIE), 1081, in press.

Kleiss, J.A., Hubbard, D.C., & Curry, D.G. (1989). Effect of three-dimensional object type and density in simulated low-level flight (AFHRL-TR-88-66). Williams AFB, AZ: Operations Training Division, Air Force Human Resources Laboratory.

Miller, K. (1984). Standardizing color CRT measurements for avionics and computers. Test and Measurement World, 4, 114-121.

Murch, G., & Virgin, L. (1985). Resolution and addressability: How much is enough? SID Digest, 16, 101-103.

Post, D.L. (1987). CRT Colorimetry System, Version 1.0 (written in Fortran for PDP-11). Wright-Patterson AFB, OH: Color Display Laboratory, Visual Display Systems Branch, Human Engineering Division, Armstrong Aerospace Medical Research Laboratory.

Post, D.L., & Calhoun, C.S. (1987). An evaluation of methods for producing specific colors on CRTs. Proceedings of the Human Factors Society, 31st Annual Meeting, 2, 1276-1280. Human Factors Society, Santa Monica, CA.

Post, D.L., & Calhoun, C.S. (1989). An evaluation of methods for producing desired colors on CRTs monitors. Color Research and Application, 14, in press.

van Meeteren, A., & Vos, J.J. (1972). Resolution and contrast sensitivity at low luminances. Vision Research, 12, 825-833.

van Nes, F.L., & Bouman, M.A. (1967). Spatial modulation transfer in the human eye. Journal of the Optical Society of America, 57, 401-406.

Wyszecki, G., & Stiles, W.S. (1982). Color science: Concepts and methods, quantitative data and formulae (2nd ed.). New York: Wiley.

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

AOI	area of interest; high-resolution central inset in the AFHRL dome display.
AVTS	Advanced Visual Technology System; image generator for real-time flight simulation. Used for both dome and dodecahedron simulators.
CIE	Commission Internationale de l'Eclairage (International Commission on Illumination).
CRT	cathode-ray tube; the common color TV or monitor.
ftL	footlambert; unit of photopic luminance, equal to 3.426 nits.
LVP	light-valve projector; an alternative to the projection CRT as a means for projecting large-screen images. A light-valve projector involves use of electronically writable and erasable slides, known as light valves, in combination with light sources and projection optics.
MHz	megahertz; a frequency measure equal to one million cycles per second.
MLVP	multiple light-valve projector; an LVP employing two sources and two light valves, projecting through common final optics.
nit	unit of photopic luminance, equal to one candela per square meter or 0.2919 ftL.
nm	nanometer = 10^{-9} meters; a length measure commonly used to specify wavelengths in the visible range of the electromagnetic spectrum (370 to 730 nm).
RGB	Red-Green-Blue; a code specifying digital bit values for the red, green, and blue primaries of a three-primary color display; values must be specified in the order red, green, blue.
SED	spectral energy distribution; a graph or list specifying the wavelength composition of a light. Either absolute or relative energy may be specified as a function of wavelength.
SLVP	single light-valve projector; an LVP with only one source and only one light valve.

SRD — spectral reflectance distribution; a graph or list specifying the spectral reflectance of a surface as a function of wavelength.

VA — visual angle; a measure of the size of a display area in terms independent of viewing distance. If the radius of a circular area is d centimeters and if the display is viewed at a distance of D centimeters, the visual angle is (d/D)57.3 degrees.

$V(\lambda)$ — luminous efficiency function for human vision under conditions of daylight or photopic illumination. This function underlies all of modern photometry.

$V'(\lambda)$ — luminous efficiency function for human vision under night or scotopic illumination; the luminous efficiency function for retinal rods.

UCS — uniform chromaticity space; a chromaticity space in which the distance between two chromaticity points is approximately proportional to the perceived hue difference between the colors which they represent.

APPENDIX A

COLORIMETRIC CONVERSION EQUATIONS

1931 CIE x, y, z from X, Y, Z:

$$x = \frac{X}{X + Y + Z} \qquad y = \frac{Y}{X + Y + Z} \qquad z = 1 - (x + y)$$

1931 X, Y, Z from 1931 x, y, Y(nits):

$$X = (x/y)Y \qquad Y = Y(\text{nits}) \qquad Z = \left(\frac{1 - x - y}{y}\right)Y$$

1976 CIE u', v' from 1931 CIE X, Y, Z:

$$u' = \frac{4X}{X + 15Y + 3Z} \qquad v' = \frac{9Y}{X + 15Y + 3Z}$$

1976 CIE u', v' from 1931 CIE x, y:

$$u' = \frac{4x}{-2x + 12y + 3} \qquad v' = \frac{9y}{-2x + 12y + 3}$$

APPENDIX B

MEASURES USED IN DESCRIBING DISPLAY CONTRAST

Contrast between light and dark phases of a periodically varying pattern may be simply described in terms of the light/dark ratio, L/D, where L is the luminance of the light phase and D is the luminance of the dark phase. L/D is a useful, common sense way of describing display contrast when the principal question of interest is: "What is the ratio between the maximum and minimum luminances possible in this display?"

Other questions about display contrast require more general measures. C_m, usually called "Michelson contrast," is designed for application to sinusoidal luminance variations around a mean luminance; therefore, it may also be called "depth of modulation." Its use is frequently extended to patterns which are not sinusoidal, such as square-wave gratings. C_m is defined as

$$C_m = \frac{L_2 - L_1}{L_2 + L_1}$$

where L_2 is the maximum luminance and L_1 is the minimum luminance.

Two other contrast measures will be found in descriptions of electronic displays. These measures are (a) the luminance ratio, L_1/L_2 (which, of course, is the inverse of the light dark ratio, L/D), and (b) the raster response, $(L_2 - L_1)/L_2$. In Figure B-1 these measures are plotted above corresponding values of C_m. Numerals above the points on the luminance ratio curve represent corresponding values of L/D.

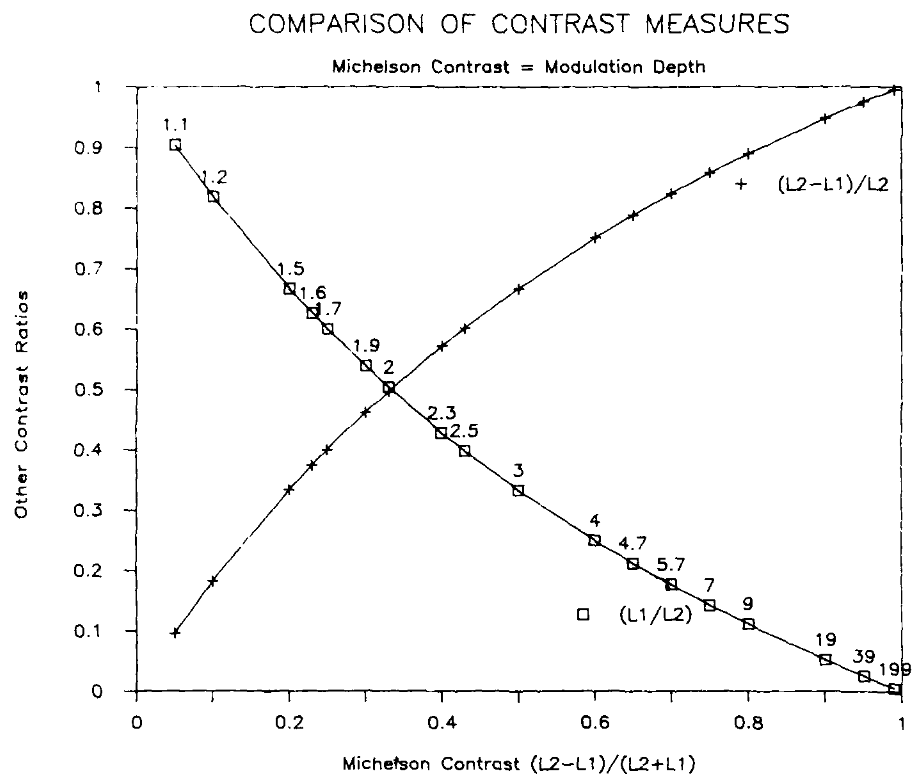


Figure B-1. Relation of L/D Ratio, Luminance Ratio, and Raster Response to Michelson Contrast.

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